Accelerator design and R&D for eRHIC

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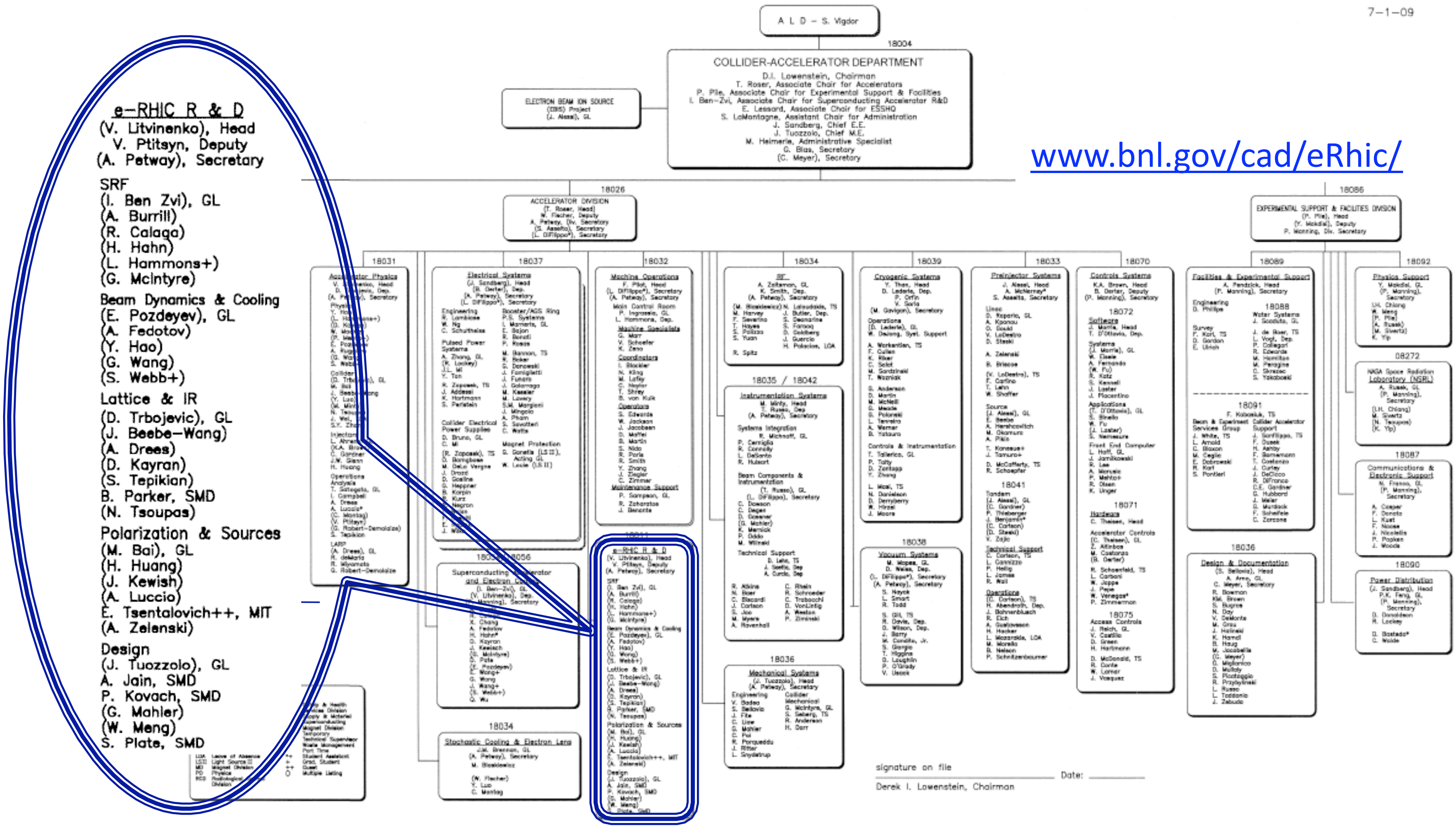
Progress

- **Continued:**
  - Development of R&D ERL
  - Small gap magnets
  - Understanding and suppression of kink instability
  - Simulation of electron beam disruption in the collision
  - Simulations of the beam-beam effects on hadron beam
- **New developments**
  - MeRHIC lattice and cost estimating
  - eRHIC staging and cost estimate
  - Coherent electron cooling for RHIC pp and eRHIC
  - Compact spreaders and combiner
  - Effects of wake-fields on beam energy loss and beam quality
  - Synchrotron radiation effects
- **Publications on eRHIC-related accelerator R&D**
  - About 25 papers in FY09 including one Phys. Rev . Lett.
  - About a dozen of invited talks at international meetings

Materials are from eRHIC R&D group and EIC task force



www.bnl.gov/cad/eRhic/

Inputs on Physics from BNL EIC task force lead by E.-C. Aschenauer, T. Ulrich,

A.Cadwell, A.Deshpande, R. Ent, T. Horn, H. Kowalsky, M. Lamont, T.W. Ludlam, R. Milner, B. Surrow, S.Vigdor, R. Venugopalan, W.Vogelsang, ….

http://www.eic.bnl.gov/taskforce.html,

eRHIC timeline

BNL & MIT

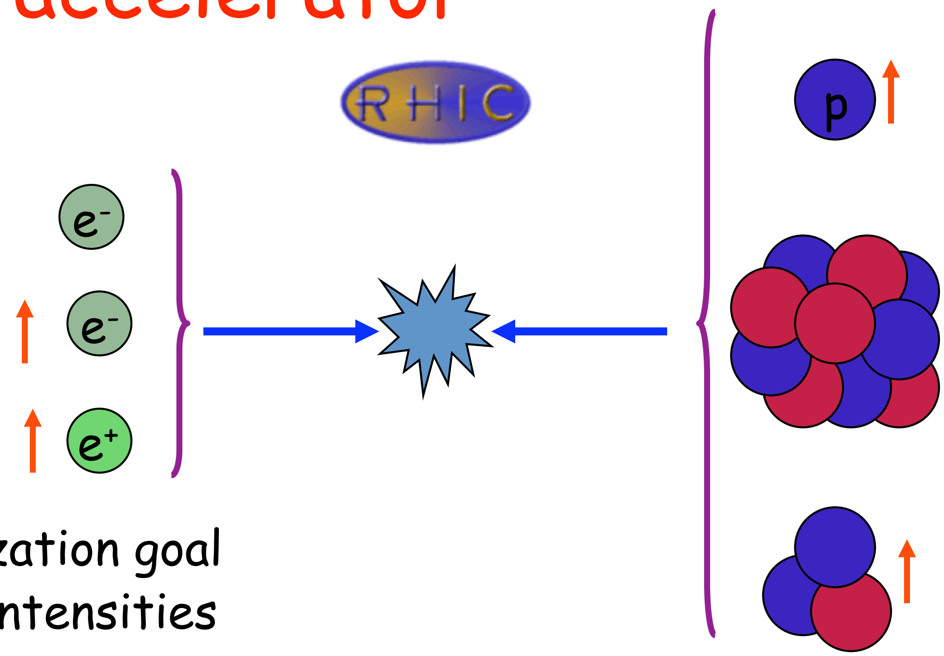
- *Add 10 GeV electron machine* to RHIC with 250 GeV polarized protons and 100 GeV/n ions
- Luminosity is based on hadron beam parameters demonstrated in RHIC complex
- First paper and workshop on eRHIC – 1999
- **"eRHIC Zeroth-Order Design Report" and cost estimate**, BNL 2004
  - Ring-ring (e-ring designed by MIT) was the main option, $L\sim10^{32}$
  - 70+ page appendix on Linac (ERL) – Ring as back-up, $L\sim10^{33}$
- 2007 – after detailed studies we found that linac-ring has 5-10 fold higher luminosity – it became the main option
- eA group made a case that 20 (or even 30 GeV) electrons are needed
- March 2008 – first staging option of eRHIC of all-in-the tunnel ERL with 2(4) GeV as the first stage, with 10 GeV and 20 GeV as next steps
  - there is potential for increase of RHIC energy to 800 GeV if physics justifies the cost
- 2009 – we work on MeRHIC (Medium energy eRHIC) design, layout and the cost estimate including the pass to full energy eRHIC, with a plan to have first release of Design Report in the Fall

eRHIC Scope -QCD Factory

Electron accelerator

Unpolarized and
polarized leptons
4-20 (30) GeV

70% beam polarization goal
Positrons at low intensities



RHIC

Polarized protons
25↓ 50-250 (325) GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 (130) GeV/u

Polarized light ions
(He^3) 215 GeV/u

Center mass energy range: 15-200 GeV

eA program for eRHIC needs as high as possible energies of electron beams even with a trade-off for the luminosity.

<u>20 GeV is absolutely essential and 30 GeV is strongly desirable</u>

<u>Potential of future energy and luminosity upgrages</u>

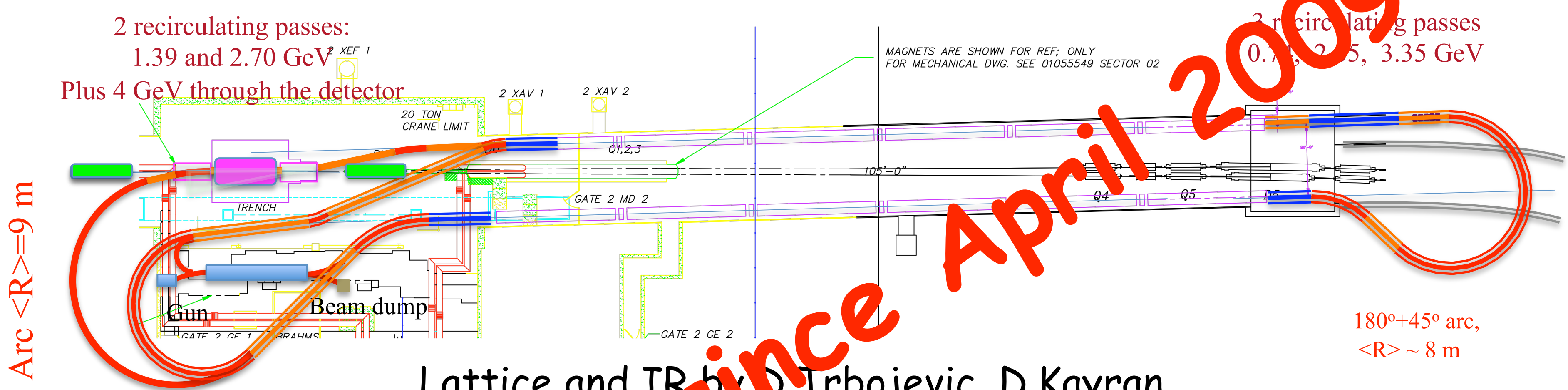
2008: Staging of eRHIC

- **MeRHIC**: Medium Energy eRHIC
  - Both Accelerator and Detector are located at IP2 of RHIC
  - 4 GeV e^- x 250 GeV p (45 or 63 GeV c.m.), L ~ 10^{32}-10^{33} cm^{-2} sec^{-1}
  - 90% of hardware will be used for HE eRHIC
- **eRHIC, High energy and luminosity phase,** inside RHIC tunnel

  Full energy, nominal luminosity

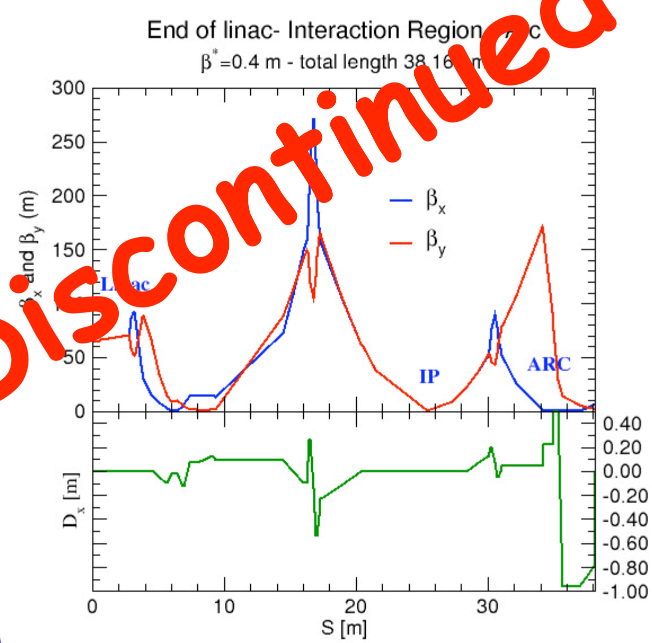
  - Polarized 20 GeV e^- x 325 GeV p (160 GeV c.m), L ~ 10^{33}-10^{34} cm^{-2} sec^{-1}
  - 30 GeV e x 120 GeV/n Au (120 GeV c.m.), ~1/5 of full luminosity
  - and 20 GeV e x 120 GeV/n Au (120 GeV c.m.), full liminosity
- **eRHIC up-grades - if needed**

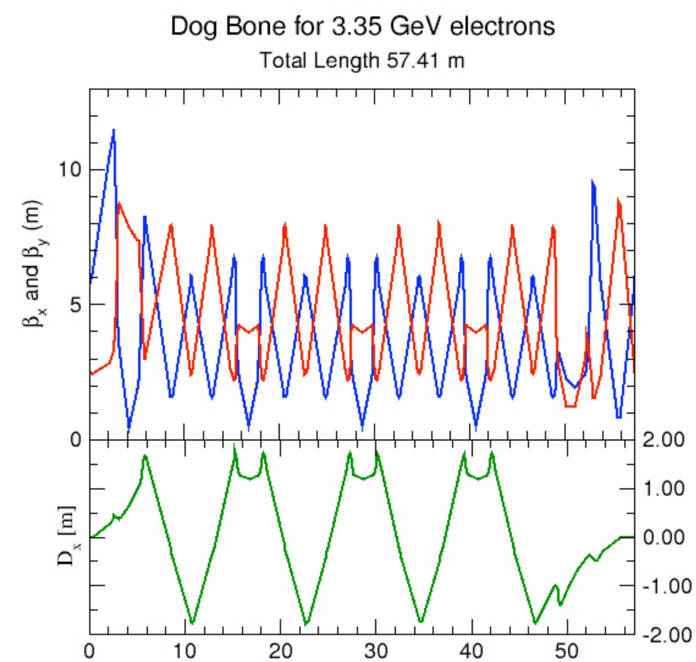
Bog-bone MeRHIC at 2 o'clock IR at RHIC (Dec. 2009)



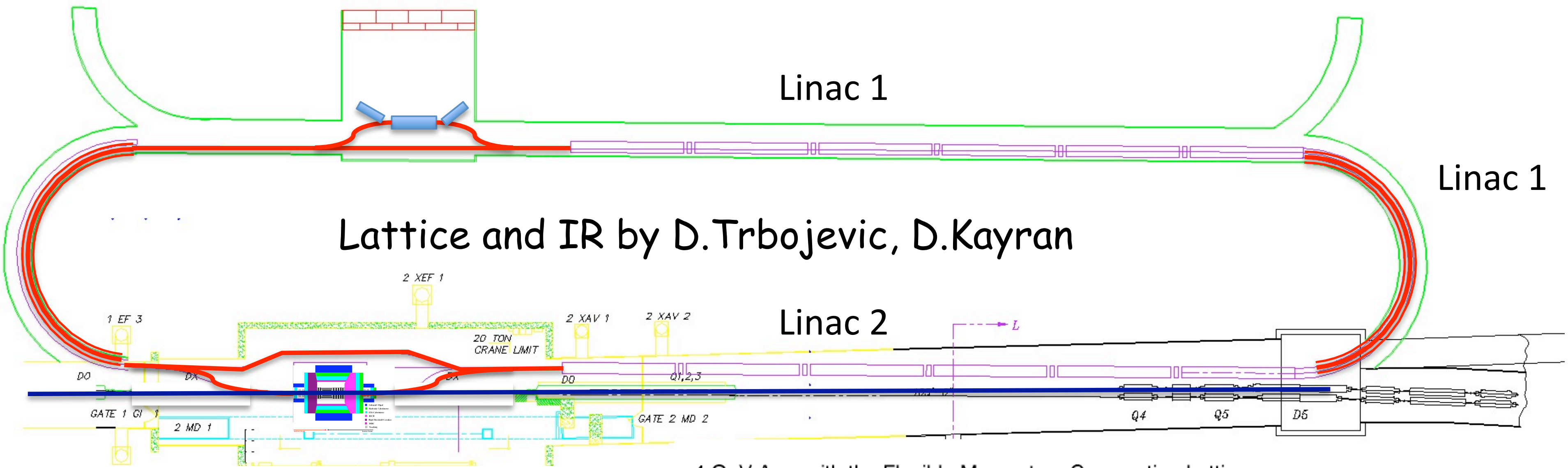
Lattice and IR by D.Trbojevic, D.Kayran

Discontinued since April 2009



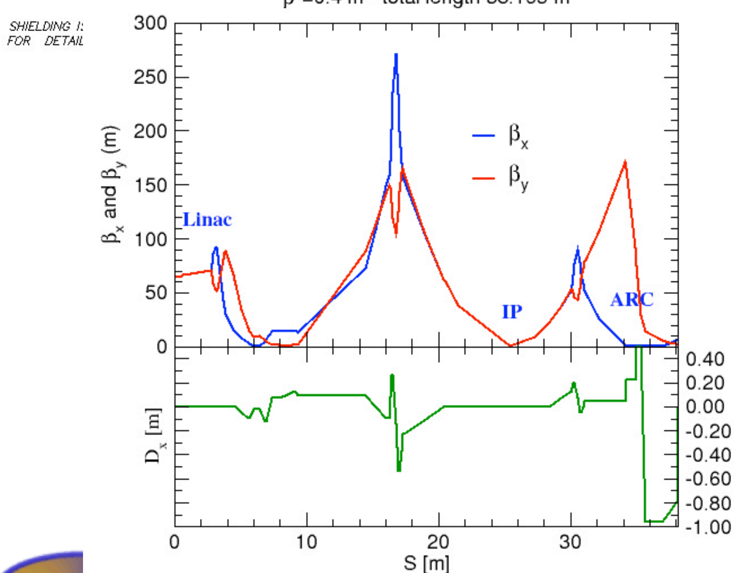


MeRHIC with 4 GeV ERL at 2 **o'clock** IR of RHIC



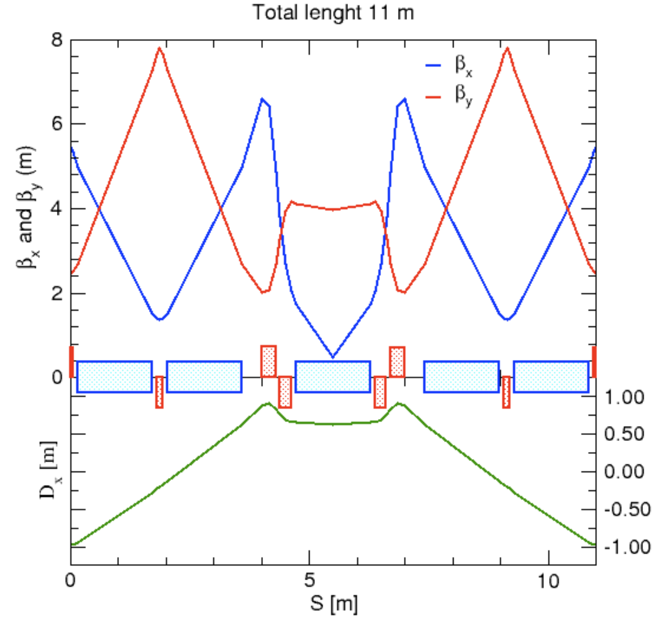
End of linac- Interaction Region - Arc

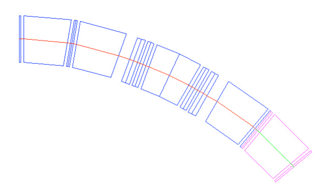
β^*=0.4 m - total length 38.165 m



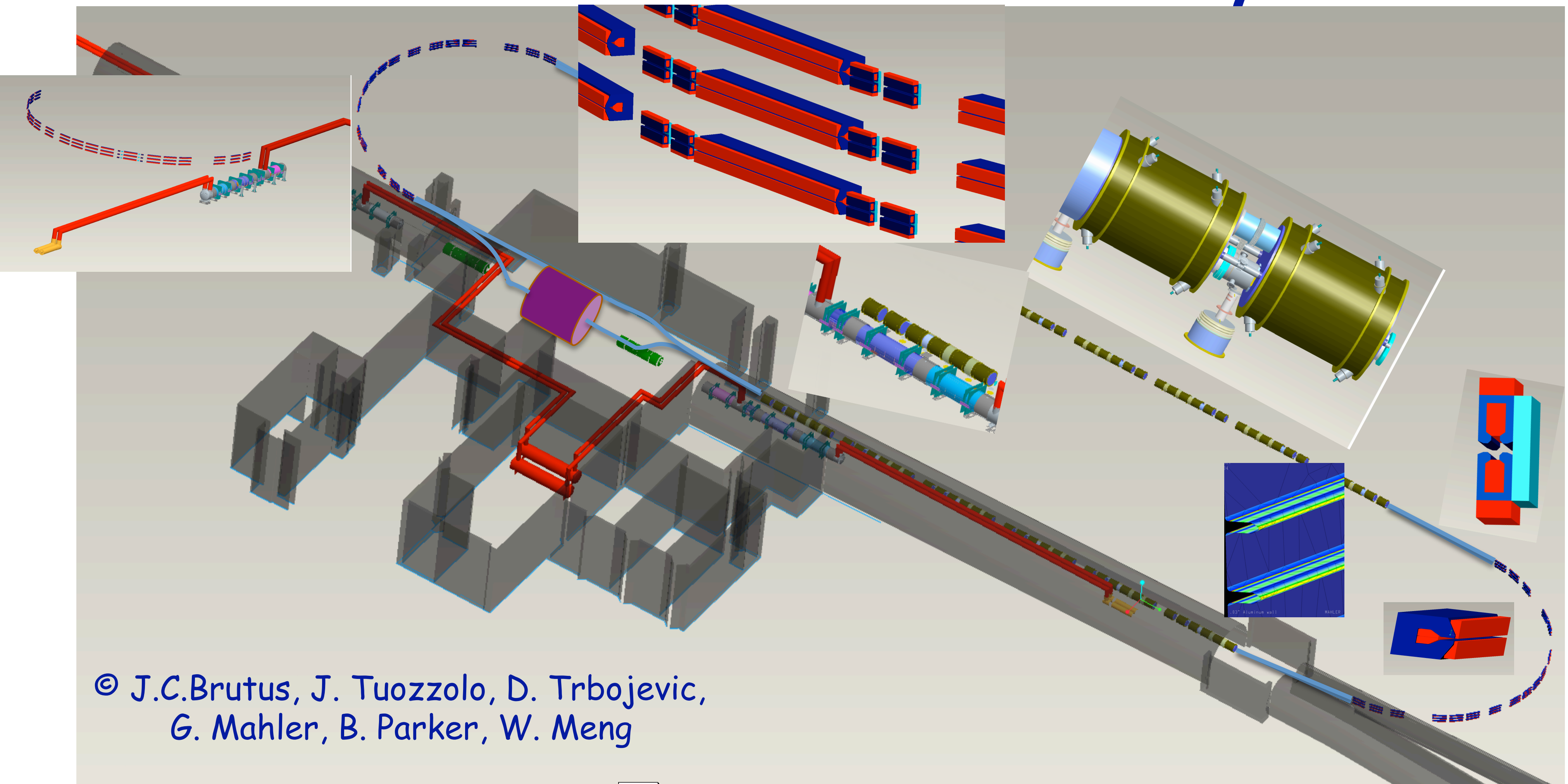
4 GeV Arcs with the Flexible Momentum Compaction Lattice

Total lenght 11 m

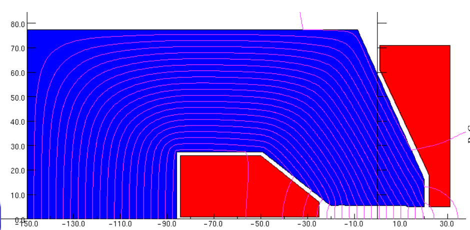


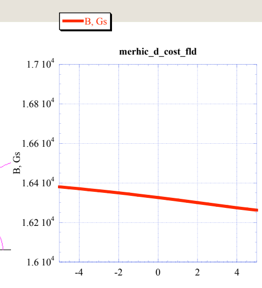


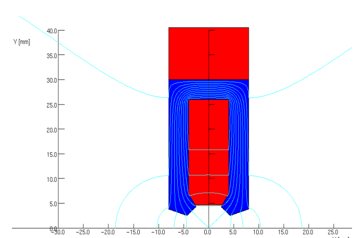
MeRHIC in IR 2: 3D layout

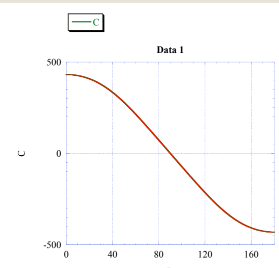


© J.C.Brutus, J. Tuozzolo, D. Trbojevic,
G. Mahler, B. Parker, W. Meng



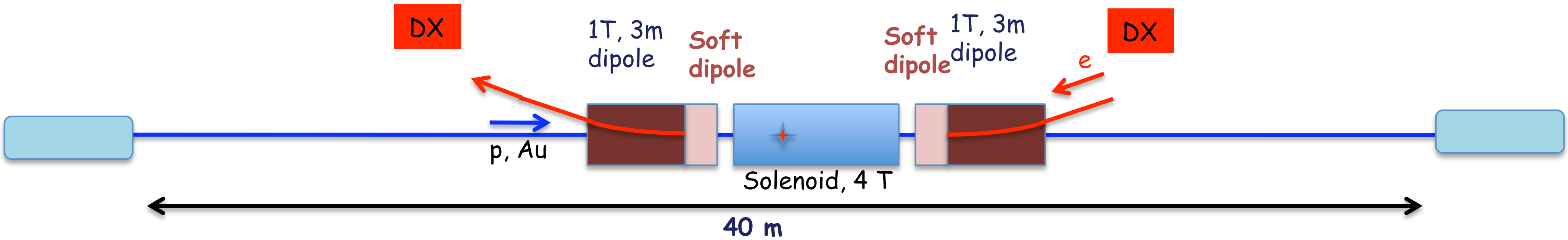


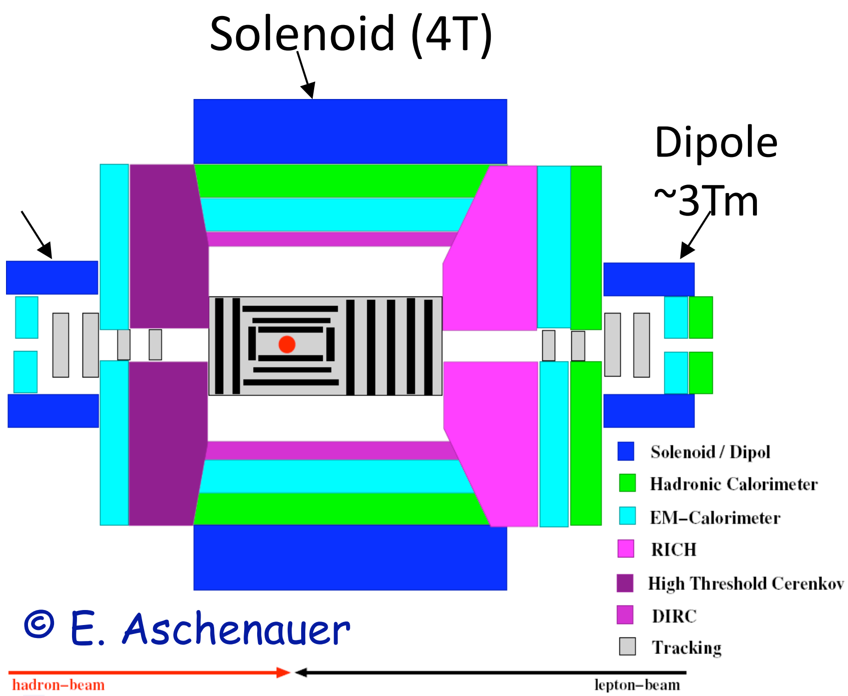




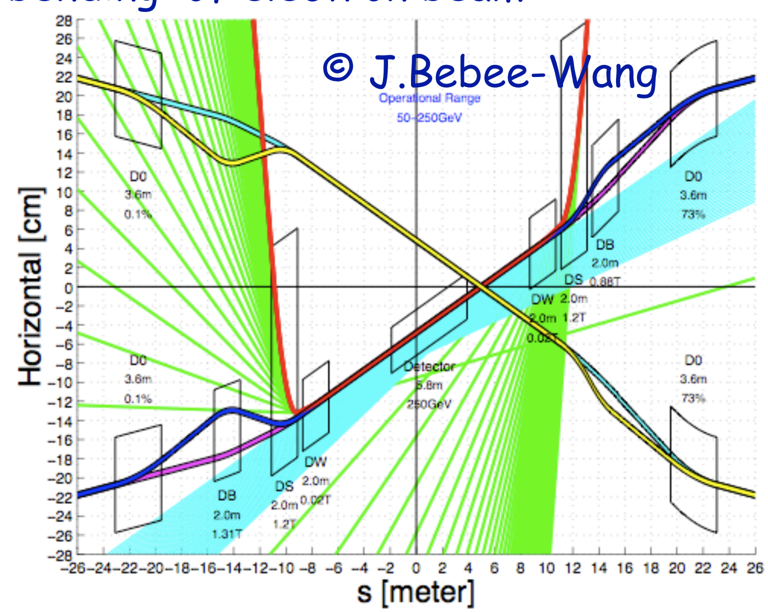
Detector field layout
MeRHIC 4 GeV e x 250 GeV p/100 GeV Au

Remove Dxes – 40 m to detect particles scattered at small angles



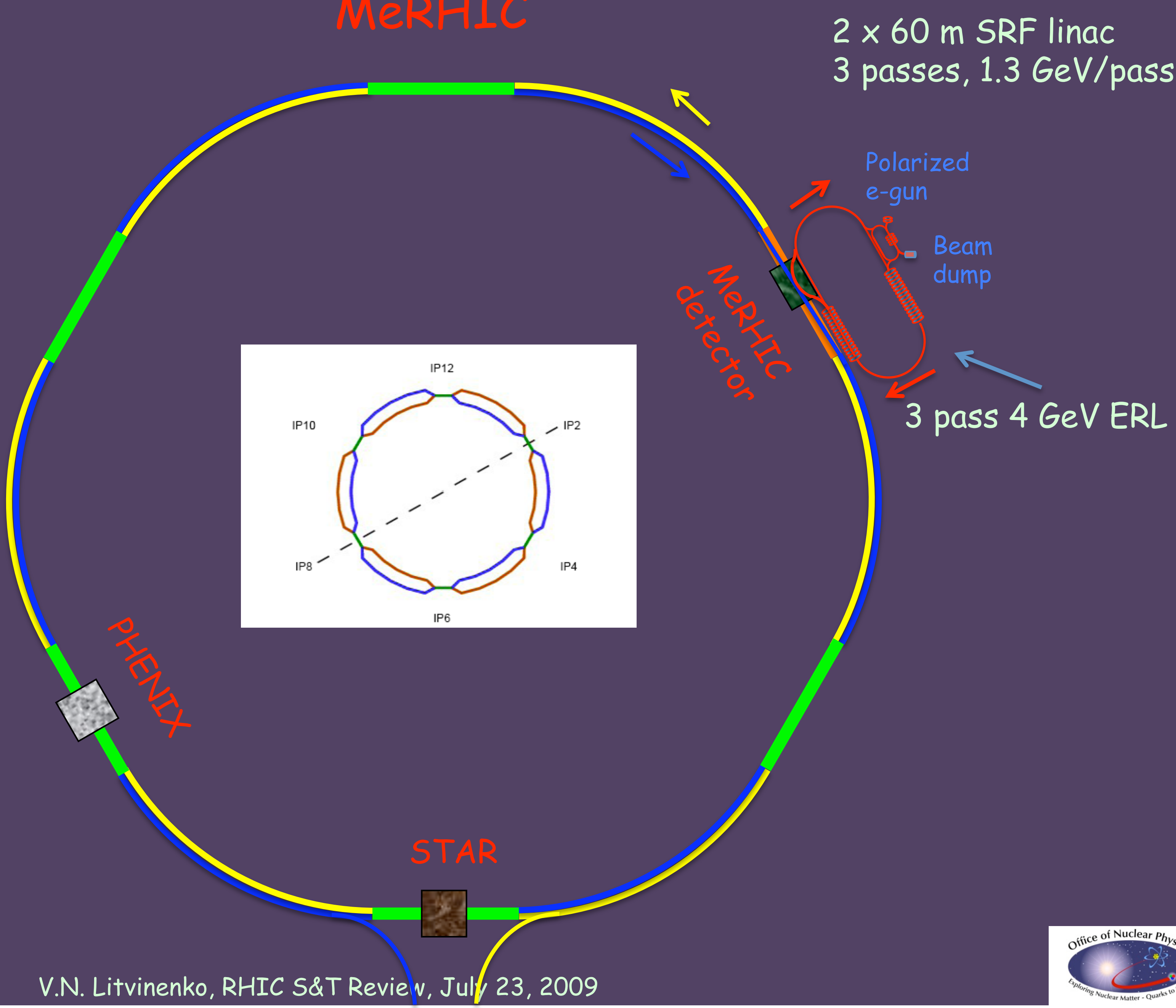


To provide effective SR protection:
-soft bend (~0.05T) is used for final bending of electron beam

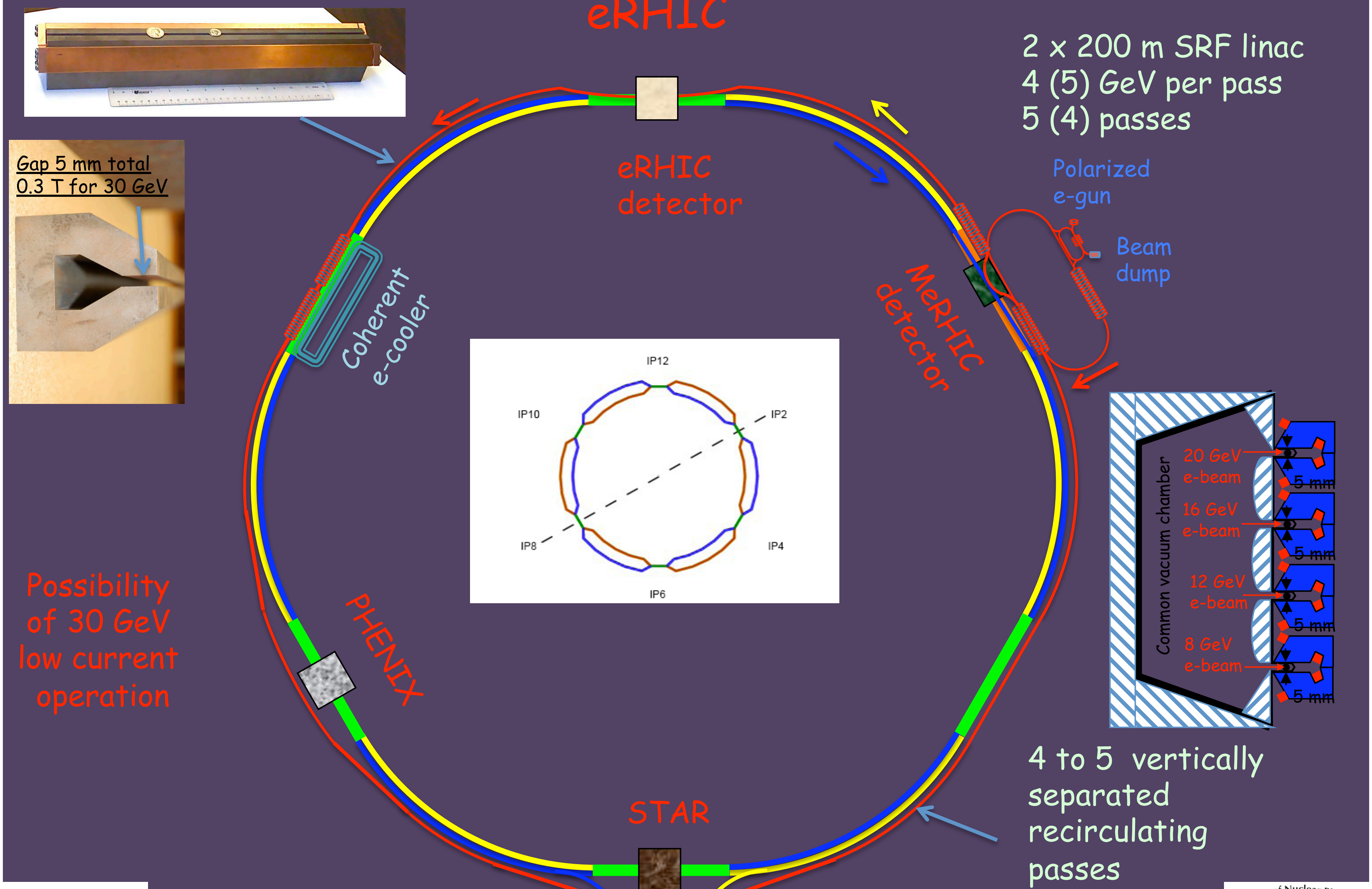


4 GeV e x 250 GeV p – 100 GeV/u Au

MeRHIC



10 to 20 GeV e x 325 GeV p – 130 GeV/u Au
eRHIC



Staging of eRHIC: Re-use, Beams and Energetics

- **MeRHIC**: Medium Energy electron-Ion Collider
  - 90% of ERL hardware will be use for full energy eRHIC
  - Possible use of the detector in eRHIC operation
- **eRHIC – High energy and luminosity phase**
  - **Based on present RHIC beam intensities**
  - With coherent electron cooling requirements on the electron beam current is 50 mA
  - 20 GeV, 50 mA electron beam losses 4 MW total for synchrotron radiation.
  - 30 GeV, 10 mA electron beam loses 4 MW for synchrotron radiation
  - Power density is <2 kW/meter and is well within B-factory limits (8 kW/m)
- **eRHIC upgrade(s) if needed**

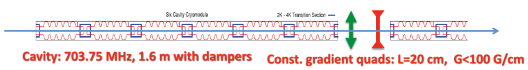
eRHIC parameters

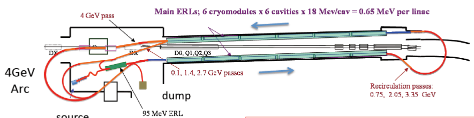
	MeRHIC		eRHIC with CeC	
	p (A)	e	p (A)	e
Energy, GeV	250 (100)	4	325 (125)	20 <30>
Number of bunches	111		166	
Bunch intensity (u) , 10^{11}	2.0	0.31	2.0 (3)	0.24
Bunch charge, nC	32	5	32	4
Beam current, mA	320	50	420	50 <5>
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.2	18
Polarization, %	70	80	70	80
rms bunch length, cm	20	0.2	4.9	0.2
β*, cm	50	50	25 (5)	25 (5)
Luminosity, × 10^{33}, $cm^{-2}s^{-1}$	0.1 -> 1 with CeC		2.8 (14)	

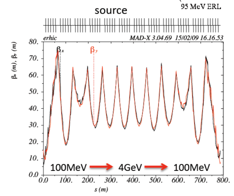
< Luminosity for 30 GeV e-beam operation will be at 20% level>

Myriad of beam dynamics issues were studied for MeRHIC
No show-stoppers !
Majority of these findings were reported at MAC meeting in March 2009
Main finding – we could operate main SRF linacs without 3rd harmonics

Linac design with const. grad quads (current baseline)







- Bunch: Q_b=5 nC, σ_z=2mm
- E_{inj}/E_{max} = 100MeV / 4GeV
- 3 acc./decel. passes
- N cavities = 72 (total)
- L module/period = 9.6 / 11.1m
- E_f = 18.0 MeV/cav
- $\langle dE/ds \rangle$ ~ 10 MeV/m

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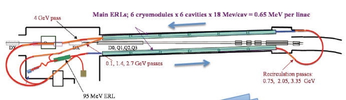
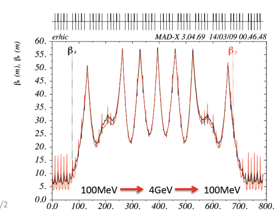
Scaled gradient solution



Scaling gradient with energy produces more focusing and increases BBU threshold

G_{min} ~ 100 G/cm — Quad strength — G_{max} ~ 500 G/cm



Scaled linac is work in progress

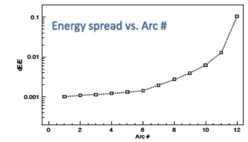
Beam losses

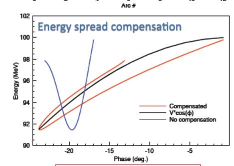
- **Touschek**
  - Total loss beyond ±6 MeV is 200 pA.
  - Small but, maybe, not negligible. We will look more carefully.
- **Scattering on residual gas (elastic)**
  - Total loss beyond 1 cm aperture at 100 MeV is 1 pA
  - Negligible
- **Bremsstrahlung on residual gas**
  - Total loss beyond ±6 MeV is < 0.1 pA
  - Negligible

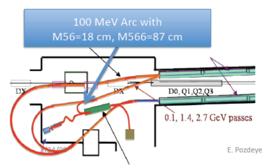
(A. Fedotov, G. Wang)

Energy spread and its compensation

	δE (MeV)
RF	0.17%
Cavity Wakes	8.9
Synch. Rad. (4•rms)	1.35
Resistive Wall	0.45
CSR	> 0.001
Total	10.7







100 MeV: 9 MeV -> 2 MeV
200 MeV: 9 MeV -> 3 MeV

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Beam-Beam: kink instability

Without Landau damping, the beam parameters are above the threshold of kink instability for proton beam. Proper energy spread and chromaticity is needed to suppress the emittance growth.

To avoid strong head-tail instability:

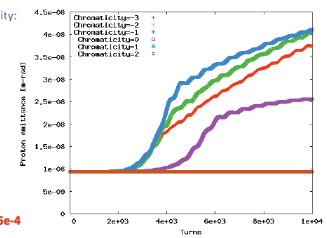
$$\frac{a\beta}{8\nu_s} < 1$$

$$a = \frac{\sigma_{pz}}{2 f_p f_z} = \frac{N_p N_e r_p r_e \sigma_{pz}}{2\sigma_{pz}^2 \sigma_{ex}^2 \gamma_p \gamma_e}$$

Not Cooled MEeIC case

$$\frac{a\beta}{8\nu_s} \sim 2.5$$

Chromaticity of 1 and dE/E of 5e-4 Suppress the instability



(Yue Hao)

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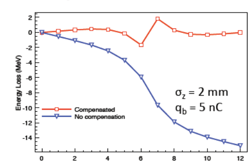
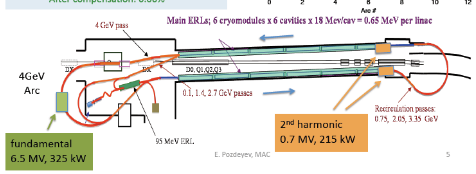
Energy loss and its compensation

- **Total energy loss: 15.5 MeV**
  - Linac cavities: 6.5 MeV (0.54 MeV/linac)
  - Synch. radiation: 8.8 MeV
  - RW: 0.15 MeV, CSR: negligible
- **Total power loss: 765 kW**
- **Energy difference in arcs (max)**
  - Before compensation: 2%
  - After compensation: 0.06%





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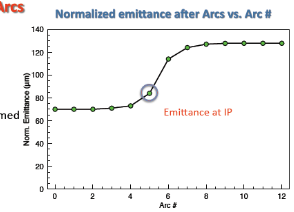
Transverse emittance growth

Synchrotron Radiation in Arcs

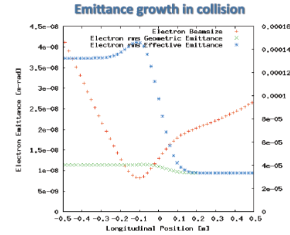
$$\delta\varepsilon = \frac{55 r_e \hbar c}{48\sqrt{3} mc^2}\gamma^5 \int_L \frac{H}{\rho^3} ds$$

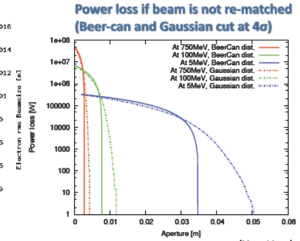
- H function of 3.35 GeV arc is used
- H function and bending radius assumed the same for all arc



Transverse breakup due to short range wakes ("banana" effect): Work in progress

Beam-Beam: electron beam disruption





(Yue Hao)

- Growth of r.m.s. emittance is small. However, mismatch is large.
- Re-matching section might be required
- Re-m
  elect

3/24/09

Summary and plans

- **Main Linac design has been developed**
  - Constant gradient: weak identical quads, similar arcs, sufficiently high BBU threshold (250 mA)
  - Scaled gradient: higher BBU threshold (900 mA)
- **Beam physics: no show stoppers so far**
- **Things to do:**
  - Continue work on compact HOM dampers
  - Explore other energy spread suppression techniques (Cornell?)
  - "Banana effect" (transverse BBU due to short range wakes)
  - Ions and ion clearing (electrodes?)
  - Requirements on noise in electron beam with realistic spectrum
  - Analysis of optics errors and nonlinearities is in progress
- **Improve accuracy of estimates, simulations.**
- **Experimental studies, if possible (BNL ERL, BNL ATF, JLab FEL, etc.)**

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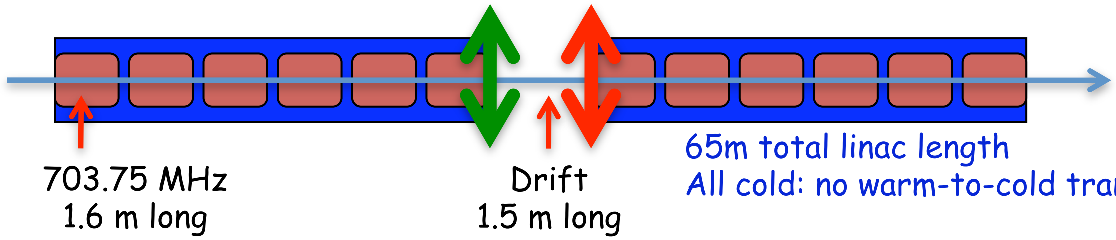
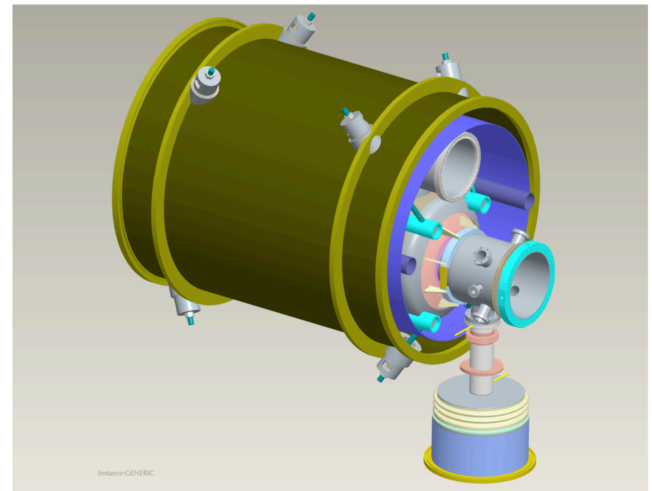
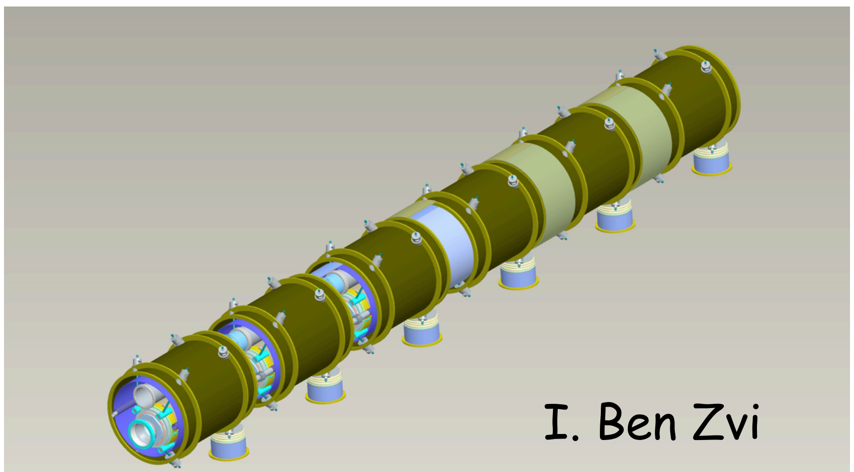
MeRHIC Linac Design



65m total linac length
All cold: no warm-to-cold transition



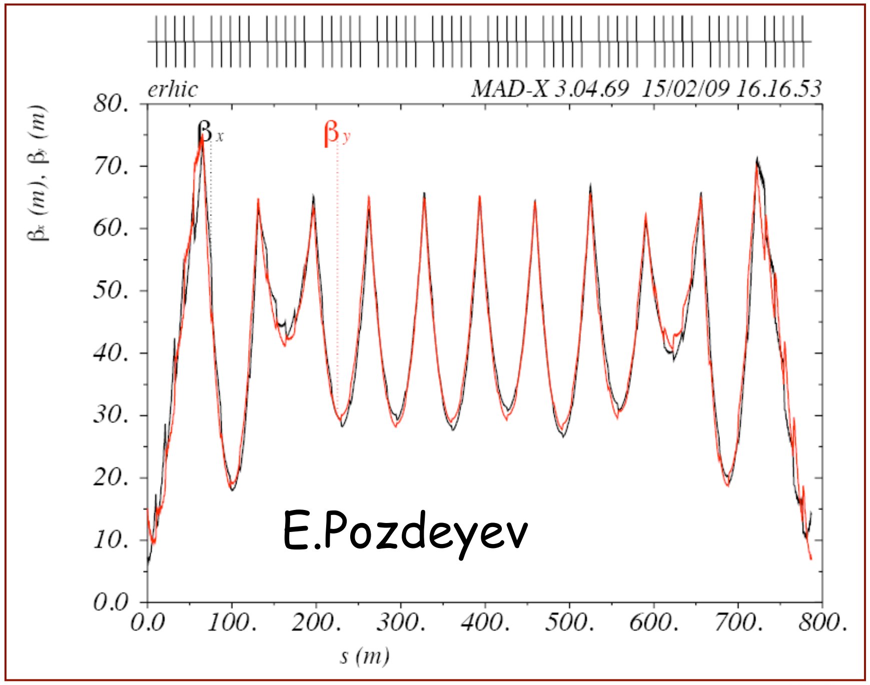


Current breakdown of the linac

- N cavities = 6 (per module)
- N modules per linac = 6
- N linacs = 2
- L module = 9.6m
- L period = 10.6 m
- E_f = 18.0 MeV/m
- $\langle dE/ds \rangle$ = 10.2 MeV/m

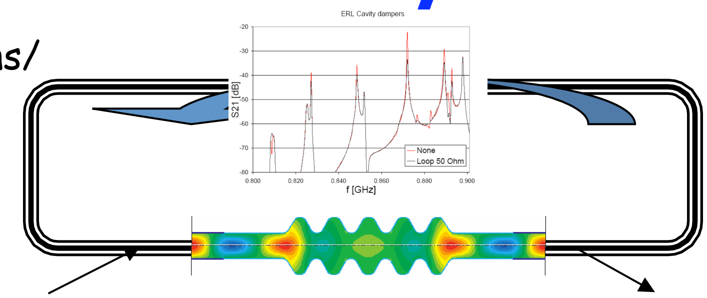
Based on BNL SRF cavity with fully suppressed HOMs
Critical for high current multi-pass ERL

100 MeV → 4 GeV → 100 MeV



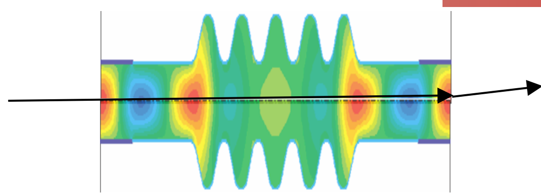
TBBU stability (©E. Pozdeyev)

- HOMs based on R. Calaga's simulations/ measurements
- 70 dipole HOM's to 2.7 GHz in each cavity
- Polarization either 0 or 90°
- 6 different random seeds
- HOM Frequency spread 0-0.001

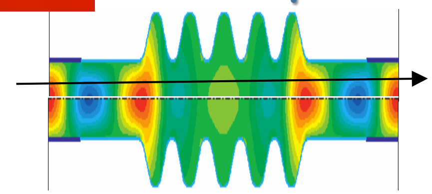


Excitation process of transverse HOM

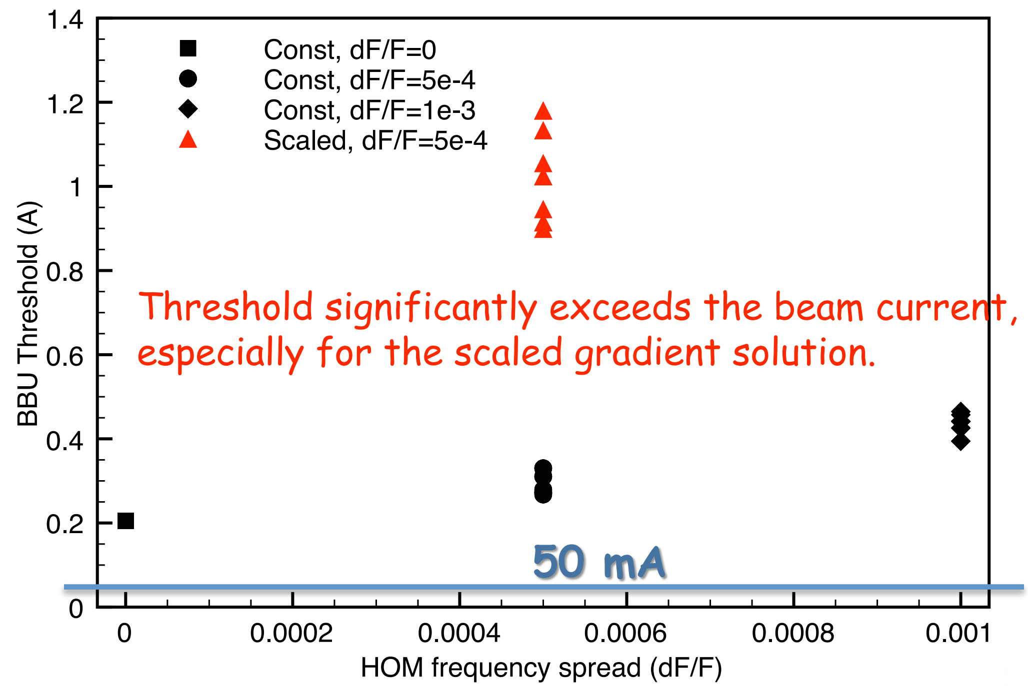
Simulated BBU threshold (GBBU) vs. HOM frequency spread.



$$\begin{bmatrix} x \\ x' \end{bmatrix}_{return} = \begin{bmatrix} m11 & m12 \\ m21 & m22 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ x' \end{bmatrix}_{comming}$$



F (GHz)	R/Q (Ω)	Q	(R/Q)Q
0.8892	57.2	600	3.4e4
0.8916	57.2	750	4.3e4
1.7773	3.4	7084	2.4e4
1.7774	3.4	7167	2.4e4
1.7827	1.7	9899	1.7e4
1.7828	1.7	8967	1.5e4
1.7847	5.1	4200	2.1e4
1.7848	5.1	4200	2.1e4



Challenges and Advantages

- Main Challenge –
  50 mA polarized gun for e-p program
- Main advantage – RHIC
  - Unique set of species from d to U
  - The only high energy polarized proton collider
  - Large size of RHIC tunnel (3.8 km)
- Main disadvantage is caused by nature
  - Ion cloud limitation of the hadron beam intensity

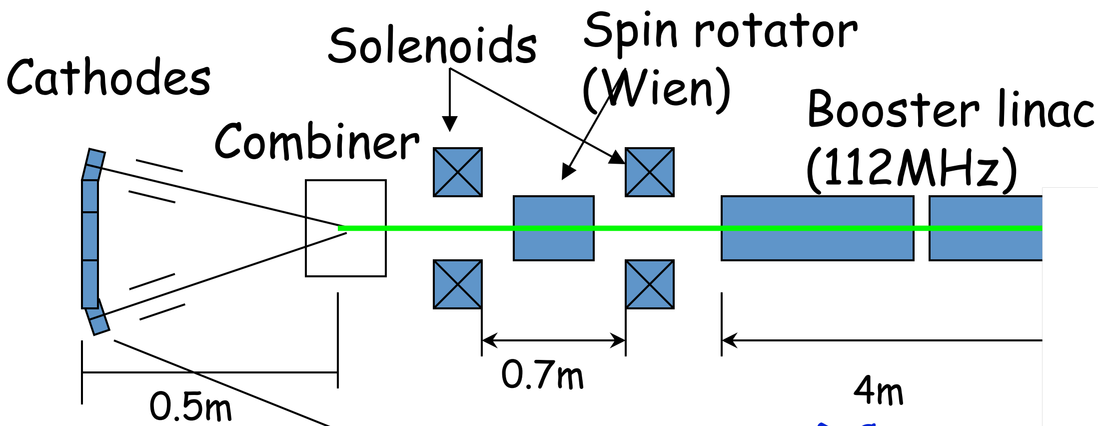
eRHIC R&D

- Polarized gun for e-p program
- Development of compact recirculating loop magnets
- ERL (more in Ilan Ben Zvi talk)
- Compact eRHIC SRF with HOM damping (more in Ilan Ben Zvi talk)
- Coherent Electron Cooling including PoP
- Polarized He^3 source

Resources in FY 2009

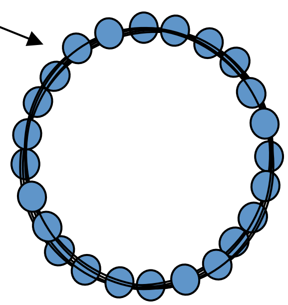
- Administrative - 1
- Scientists (include. 2 PhD students) - 8
- Professionals – 3
- Technicians – 4
- **Total** - **16**

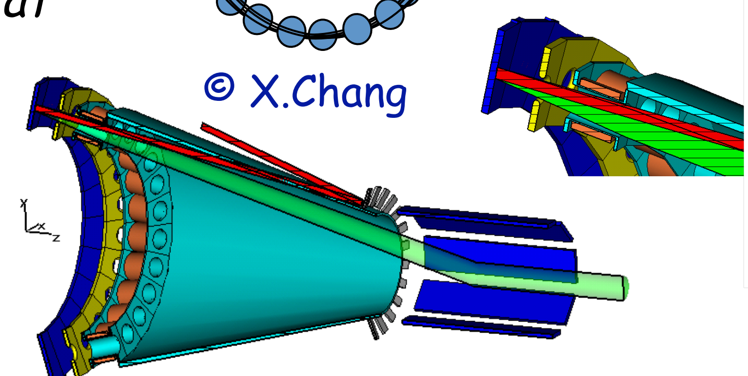
Main technical challenge is 50 mA CW polarized gun: we are building it



DC gun with 24 cathodes

Based on demonstrated current technology developed at JLab





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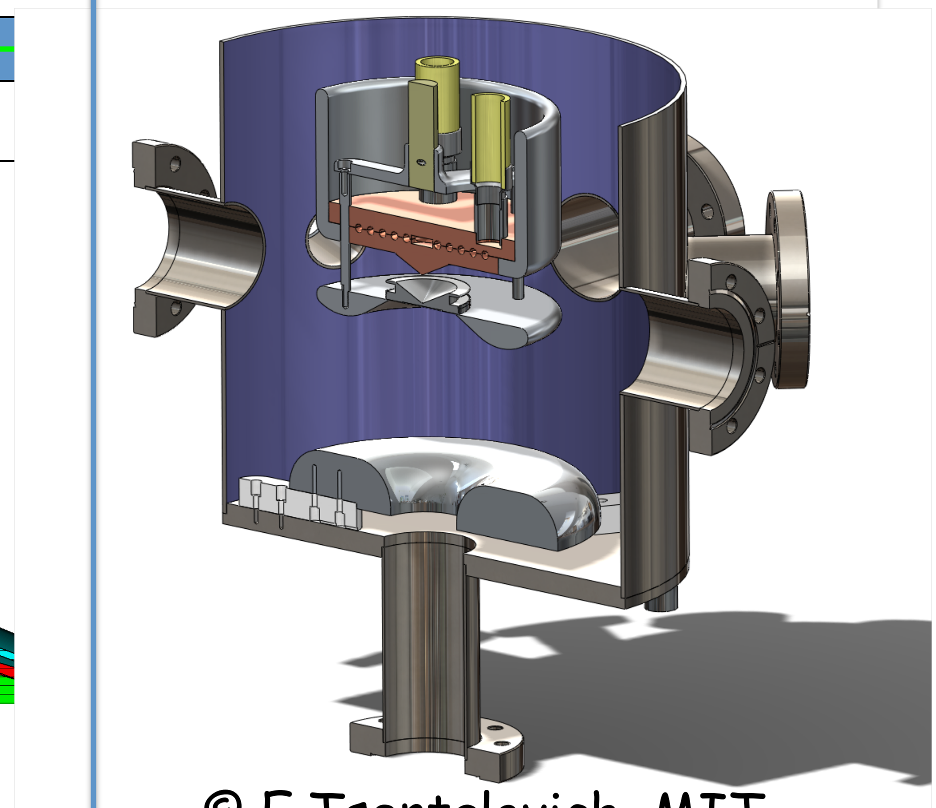
Single cathode DC gun



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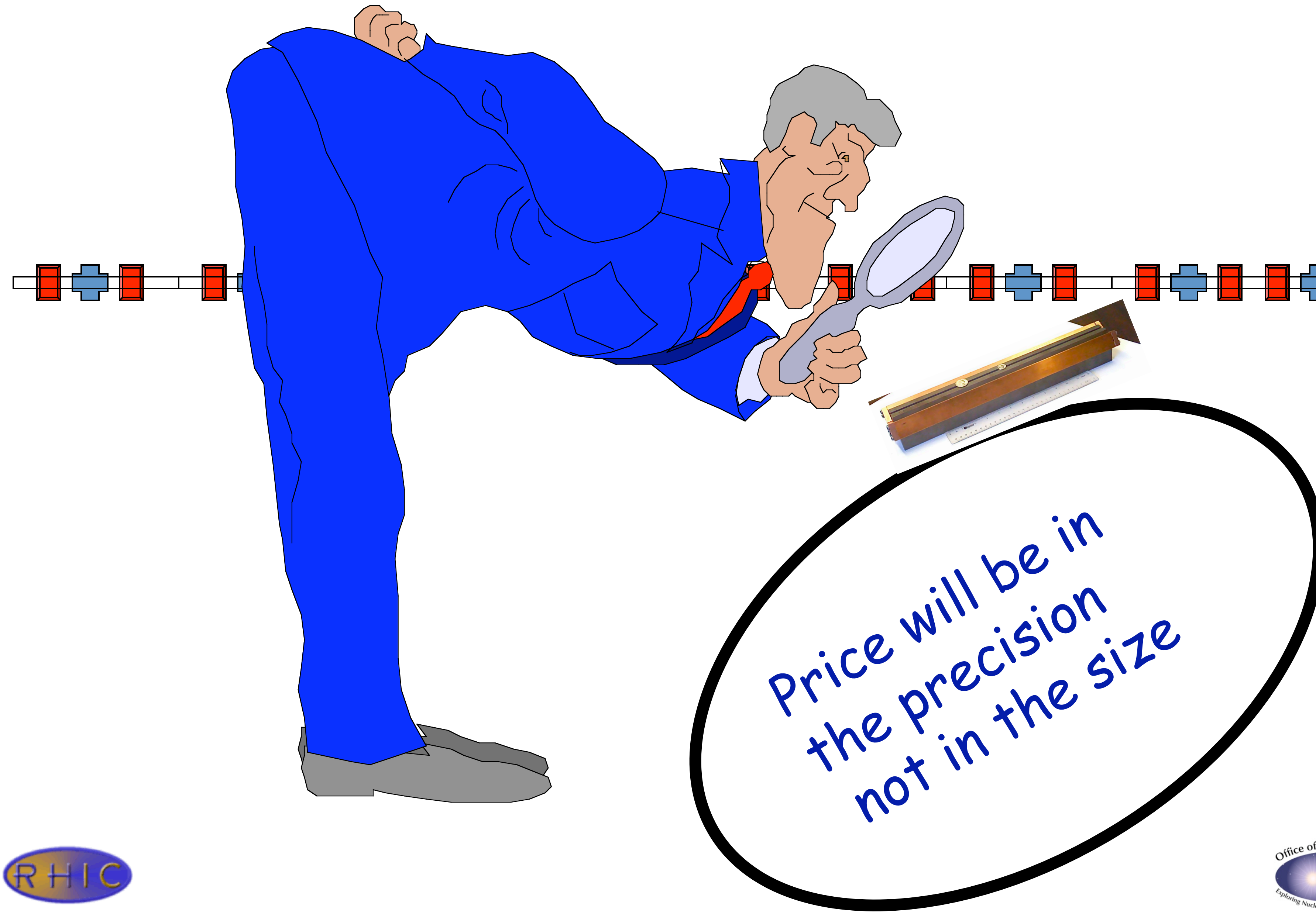
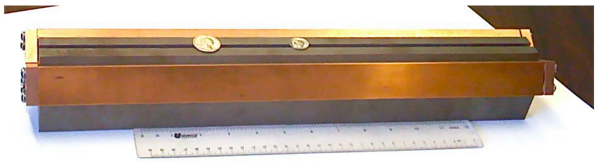
eRHIC

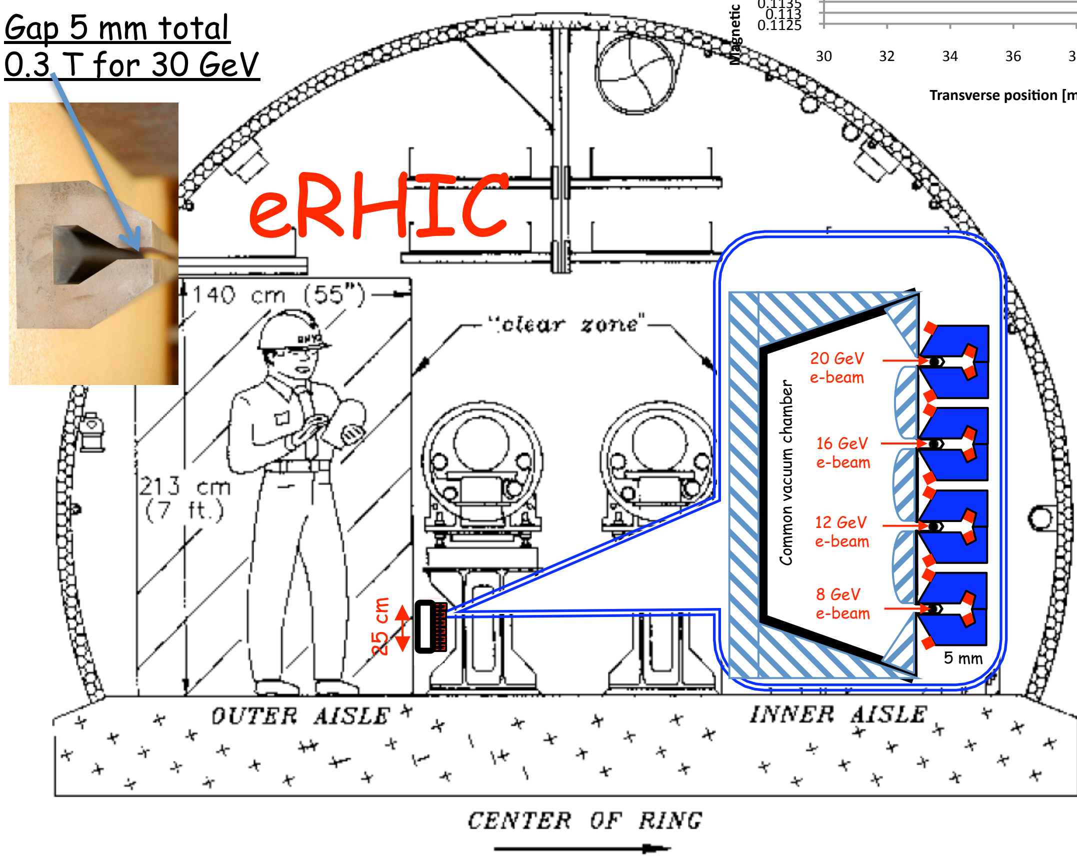


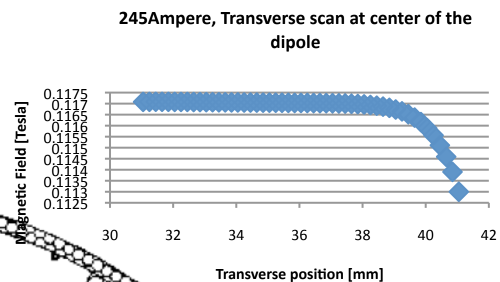
eRHIC loop magnets: LDRD project

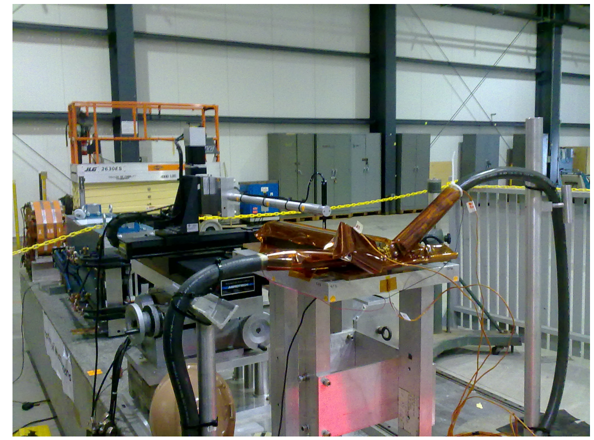
- Small gap provides for low current, low power consumption magnets
  - -> low cost eRHIC
  - Dipole prototype is under tests
  - Quad and vacuum chamber are in advanced stage

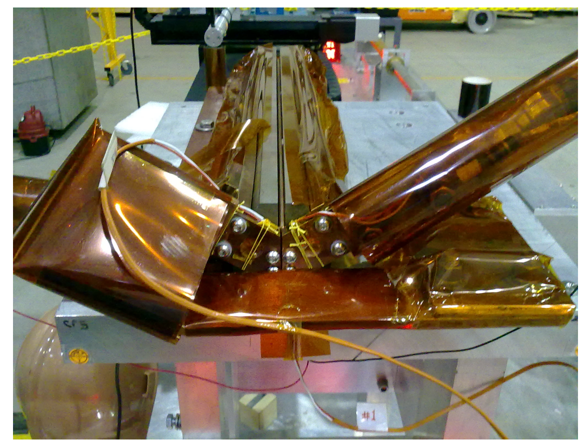


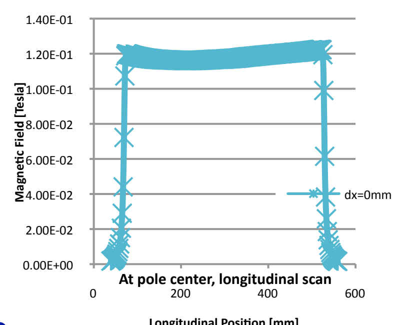
Gap 5 mm total
0.3 T for 30 GeV











©, G. Mahler, W. Meng, A. Jain, P. He, Y.Hao

V.N. Litvinenko, RHIC S&T Review, July 23, 2009

eRHIC targeted LDRD-proposals

- Accelerator:
  - Proof of principle for a gatling gun polarized electron source
    PI: Ilan Ben-Zvi
  - laser development for polarized electron source
    PI: Treveni Rao
  - undulator development for coherent electron cooling
    PI: Vladimir Litvinenko
  - polarized ^{3}He source development
    PI: Anatoli Zelenski
- Physics / Detector:
  - eA event generator development
    PI: Thomas Ullrich
  - silicon sensor development for compact EM calorimetry
    PI: Eduard Kistenev
  - Roman Pot development for eA/ep diffractive experiments
    PI: Wlodek Guryn

E.C. Aschenauer

Conclusions

- eRHIC designs provide for both polarized e-p and unpolarized eA collisions with high luminosity ~ 10^{32}-10^{34} $cm^{-2}sec^{-1}$
  - eRHIC choice of ERL for electron acceleration provides higher luminosity compared with ring-ring scenario
  - eRHIC's ERL has a natural staging strategy with increasing the energy of of the ERL is increasing length of linacs and the number of passes
  - if physics justify the cost – RHIC could be upgraded to 800 GeV by replacing magnets in one of its rings with LHC-class
  - MeRHIC technical design and cost estimate are progressing with plan to complete first release in Fall 2009

Back up

Gains from coherent e-cooling:

Coherent Electron Cooling vs. IBS

PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

$$X=\frac{\varepsilon_x}{\varepsilon_{xo}};\ S=\left(\frac{\sigma_s}{\sigma_{so}}\right)^2=\left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$

$$\frac{dX}{dt}=\frac{1}{\tau_{IBS\perp}}\frac{1}{X^{3/2}S^{1/2}}-\frac{\xi_\perp}{\tau_{CeC}}\frac{1}{S};$$

$$\frac{dS}{dt}=\frac{1}{\tau_{IBS//}}\frac{1}{X^{3/2}Y}-\frac{1-2\xi_\perp}{\tau_{CeC}}\frac{1}{X};$$

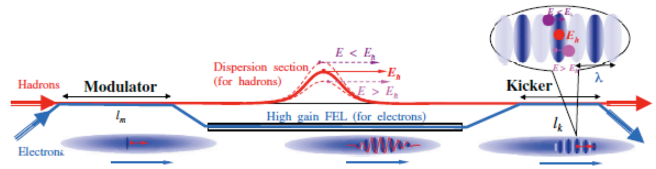


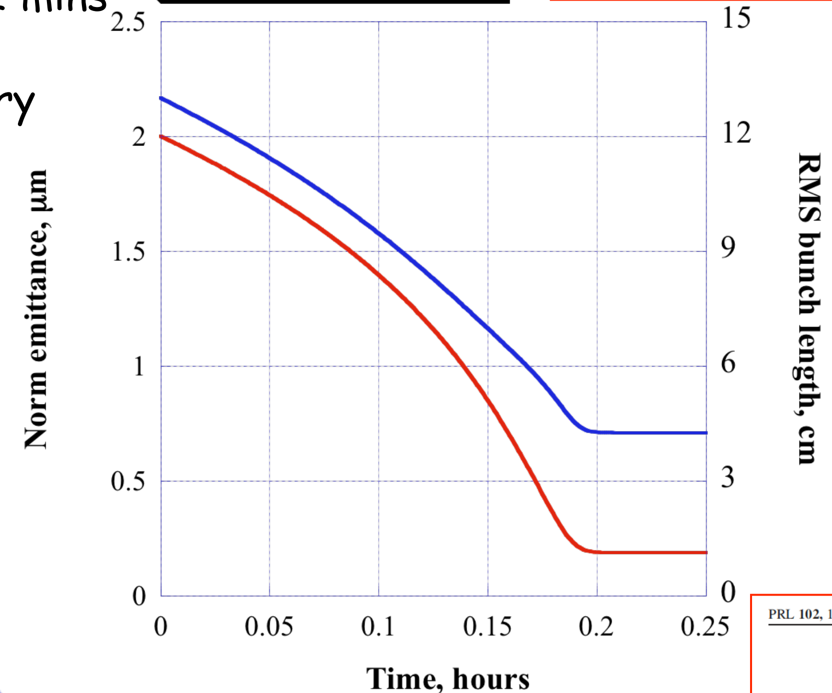
FIG. 1 (color). A general schematic of the Coherent Electron Cooler (CEC) comprising three sections: A modulator; a FEL plus a dispersion section; and, a kicker. The FEL wavelength, λ, in the figure is grossly exaggerated for visibility.

$$X=\frac{\tau_{CeC}}{\sqrt{\tau_{IBS//}\tau_{IBS\perp}}}\frac{1}{\sqrt{\xi_\perp(1-2\xi_\perp)}};\quad S=\frac{\tau_{CeC}}{\tau_{IBS//}}\cdot\sqrt{\frac{\tau_{IBS\perp}}{\tau_{IBS//}}}\cdot\sqrt{\frac{\xi_\perp}{(1-2\xi_\perp)^3}}$$

$$\varepsilon_{xn0}=2\,\mu m;\ \sigma_{s0}=13\ cm;\ \sigma_{\delta 0}=4\cdot 10^{-4}$$
$$\tau_{IBS\perp}=4.6\ hrs;\ \tau_{IBS//}=1.6\ hrs;$$

IBS in RHIC for eRHIC, 250 GeV, $N_p=2\cdot 10^{11}$
Beta-cool, ©A.Fedotov

Dynamics:
Takes 12 mins to reach stationary point



$$\varepsilon_{xn}=0.2\,\mu m;\ \sigma_s=4.9\ \ cm$$

This allows

a) keep the luminosity as it is
b) reduce polarized beam current down to 25 mA (5 mA for e-I)
c) increase electron beam energy to 20 GeV (30 GeV for e-I)
d) increase luminosity by reducing β^* from 25 cm down to 5 cm

PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

Coherent Electron Cooling

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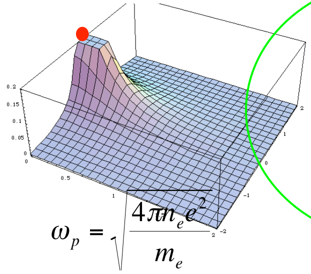
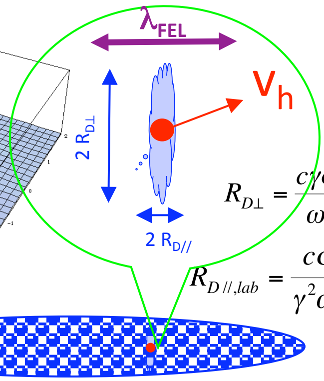
(Received 24 September 2008; published 16 March 2009)

Coherent electron cooling

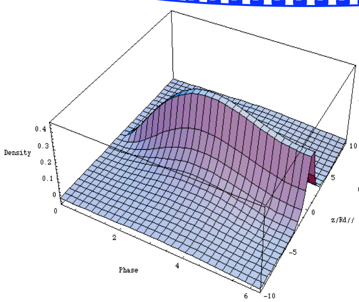


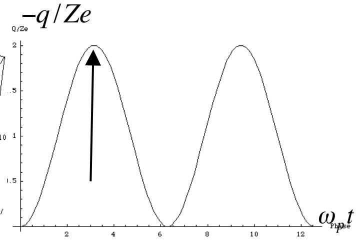


$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

$$R_{D\perp} = \frac{c\gamma\sigma_{\theta e}}{\omega_{pe}} > R_{D//}$$

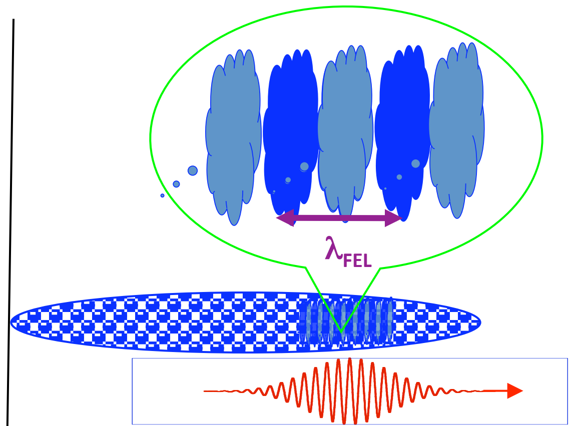
$$R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma^2\omega_{pe}} << \lambda_{FEL}$$





$$q = -Ze\cdot(1-\cos\omega_p t)$$

$$\varphi_1 = \omega_p L_1 / c\gamma$$

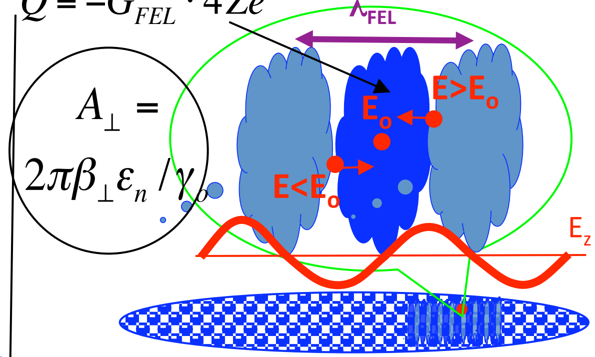


$$\lambda_{FEL} = \frac{\lambda_w}{2\gamma^2}(1+a_w^2) \qquad L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}}$$

$$L_G = L_{Go}(1+\Lambda) \qquad \Delta\varphi = \frac{L_{FEL}}{\sqrt{3}L_G}$$

$$G_{FEL} = e^{L_{FEL}/L_G}$$

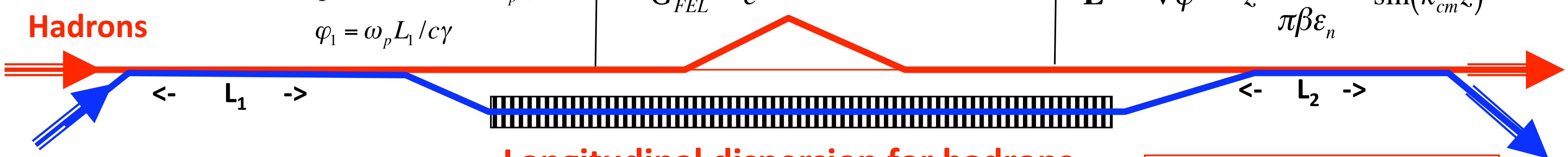
$$Q = -G_{FEL}\cdot 4Ze$$



$$k_{cm} = \frac{\pi}{\gamma_o\lambda_{FEL}} \qquad \boxed{\rho_{amp} = \frac{G\cdot Ze}{2\pi\beta\varepsilon_n}\cdot\frac{4k_{cm}}{\pi}\cos(k_{cm}z)}$$

$$\Delta\varphi = 4\pi\rho \Rightarrow \varphi = -\frac{8G\cdot Ze}{\pi\beta\varepsilon_n k_{cm}}\cdot\cos(k_{cm}z)$$

$$\vec{\mathbf{E}} = -\vec{\nabla}\varphi = -\hat{z}\frac{8G\cdot Ze}{\pi\beta\varepsilon_n}\cdot\sin(k_{cm}z)$$



Longitudinal dispersion for hadrons

$$Q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

$$Q_{\lambda_{FEL}}(\max) \approx -2Ze;\ \rho_k = -Ze\frac{4k}{\pi A_\perp}$$

$$\Delta t = -D\cdot\frac{\gamma-\gamma_o}{\gamma_o};\ D = D_{free} + D_{chicane};$$

$$D_{free} = \frac{L}{\gamma^2};\ \ D_{chicane} = l_{chicane}\cdot\theta^2$$

$$\boxed{\Delta E_i = -\frac{8G\cdot Z^2e^2}{\pi\beta\varepsilon_n}L_2\cdot\sin\left(k_{FEL}D\frac{E-E_o}{E_o}\right)\cdot\left(\frac{\sin\varphi_2}{\varphi_{p2}}\right)\cdot\left(\sin\frac{\varphi_1}{2}\right)^2}$$

Modulator:region 1 a quarter to a half of plasma oscillation

Amplifier of the e-beam modulation via FEL with gain G_{FEL}~10^2-10^3

Kicker: region 2, less then a quarter of plasma oscillation

RHIC

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

ERL spin transparency at all energies

Bargman, Mitchel,Telegdi equation

$$\frac{d\hat{s}}{dt} = \frac{e}{mc}\hat{s}\times\left[\left(\frac{g}{2}-1+\frac{1}{\gamma}\right)\vec{B} - \frac{\gamma}{\gamma+1}\left(\frac{g}{2}-1\right)\vec{\beta}\left(\vec{\beta}\cdot\vec{B}\right) - \left(\frac{g}{2}-\frac{\gamma}{\gamma+1}\right)\left[\vec{\beta}\times\vec{E}\right]\right]$$

$$a = g/2-1 = 1.1596521884\cdot 10^{-3}$$

$$\hat{\mu} = \frac{g}{2}\frac{e}{m_o}\hat{s} = (1+a)\frac{e}{m_o}\hat{s}; \qquad \nu_{spin} = a\cdot\gamma = \frac{E_e}{0.44065[GeV]}$$

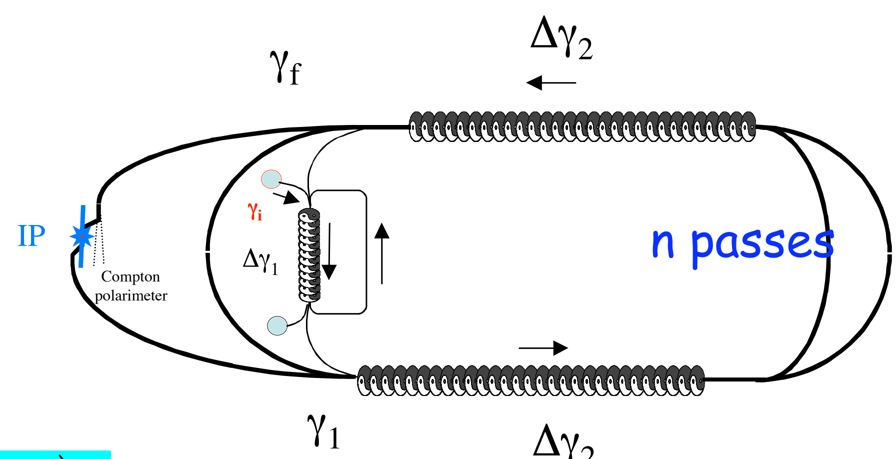
$$\Downarrow$$

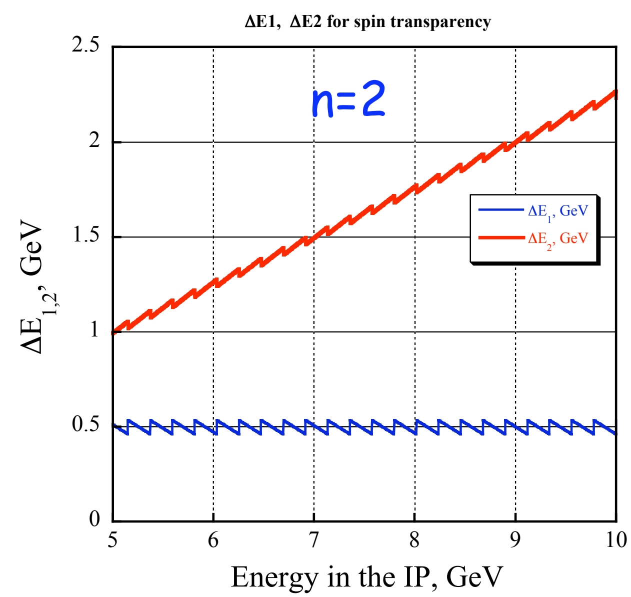
$$\Delta\varphi = a\cdot\gamma\theta$$

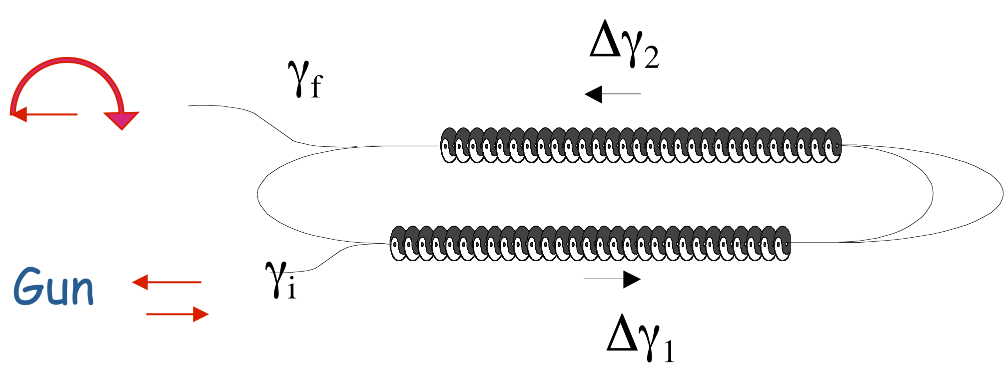
Total angle $\varphi = \pi a\cdot\left(\gamma_i(2n-1) + n(\Delta\gamma_1\cdot n + \Delta\gamma_2(n-1)\right)$

Has solution for all energies!

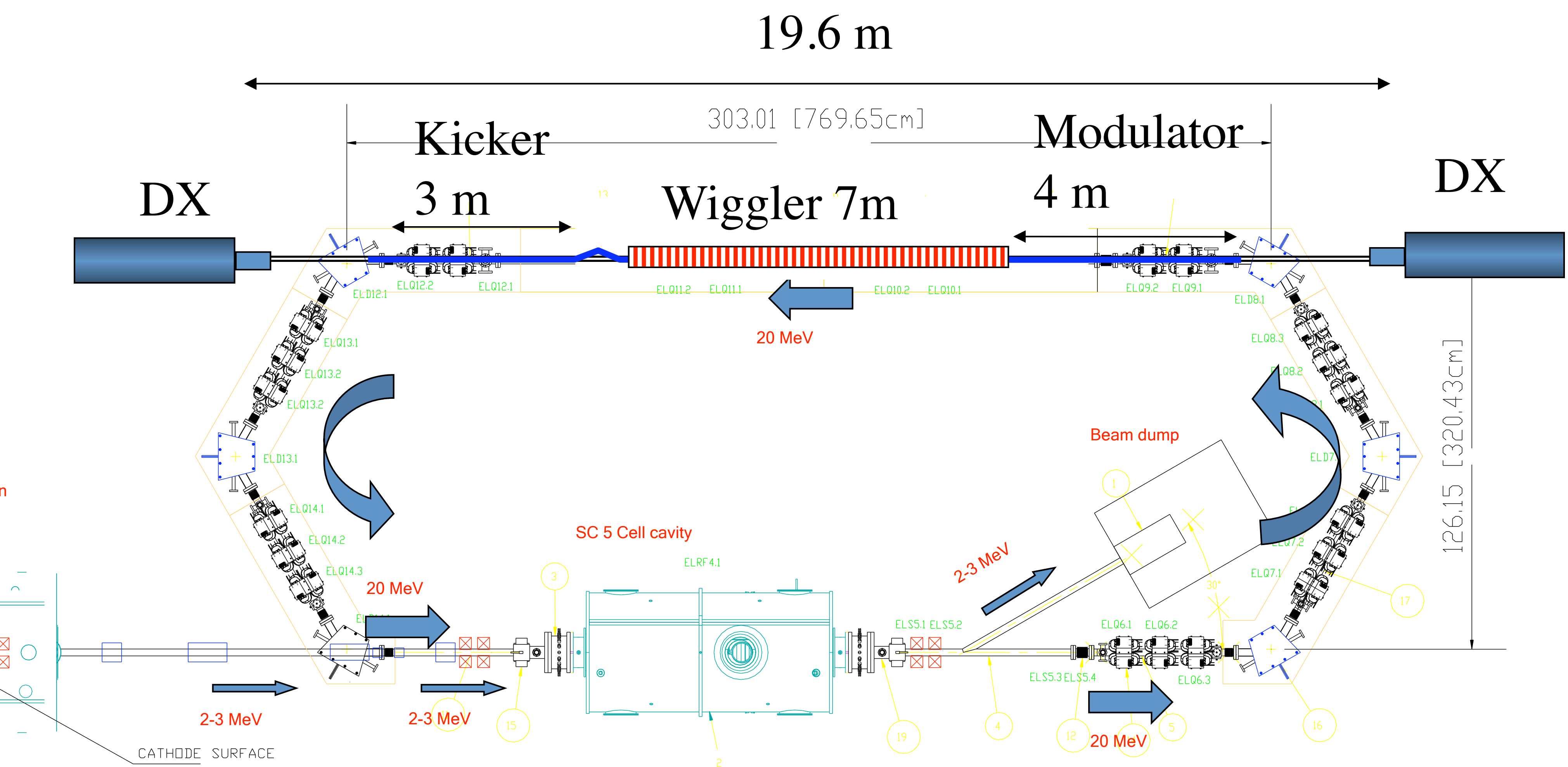
$$\begin{Bmatrix} \gamma_i + 2\cdot(\Delta\gamma_1+\Delta\gamma_2) & = \gamma_f \\ a\cdot\left(\gamma_i(2n-1) + n(\Delta\gamma_1\cdot n + \Delta\gamma_2(n-1)\right) & = N \end{Bmatrix}$$



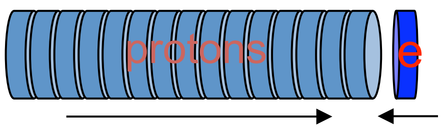


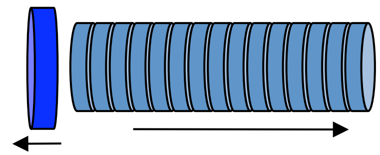


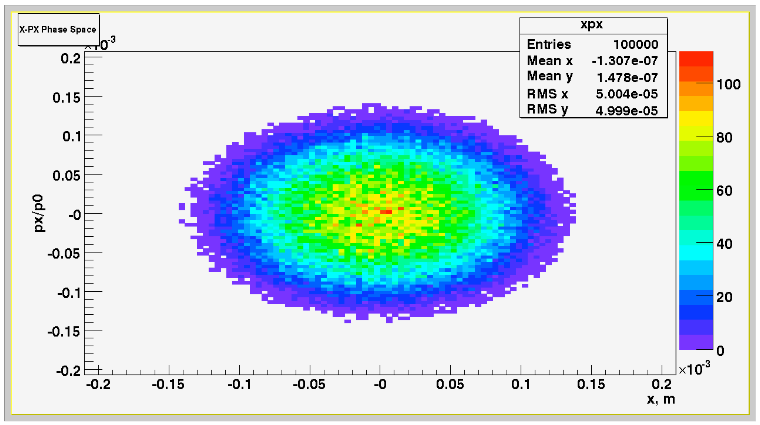
IR-2 layout for Coherent Electron Cooling proof-of-principle experiment



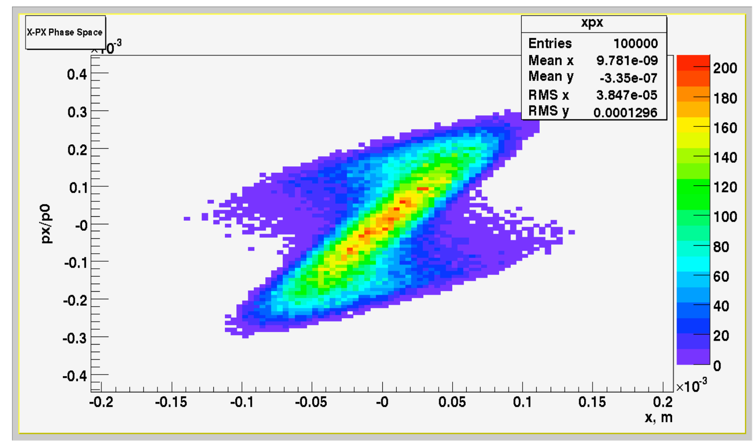
Beam Disruption



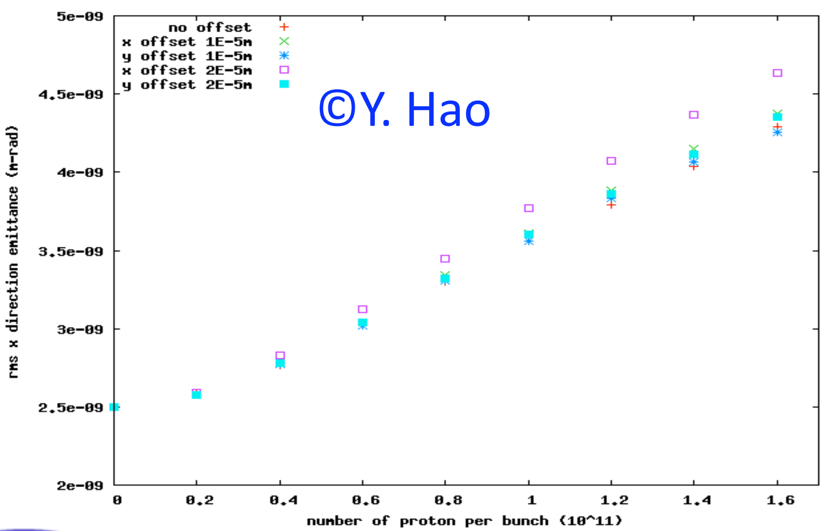


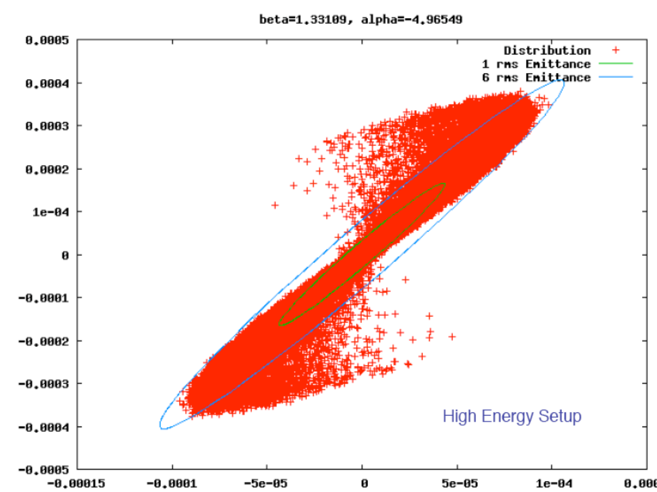


Interaction



Optimized





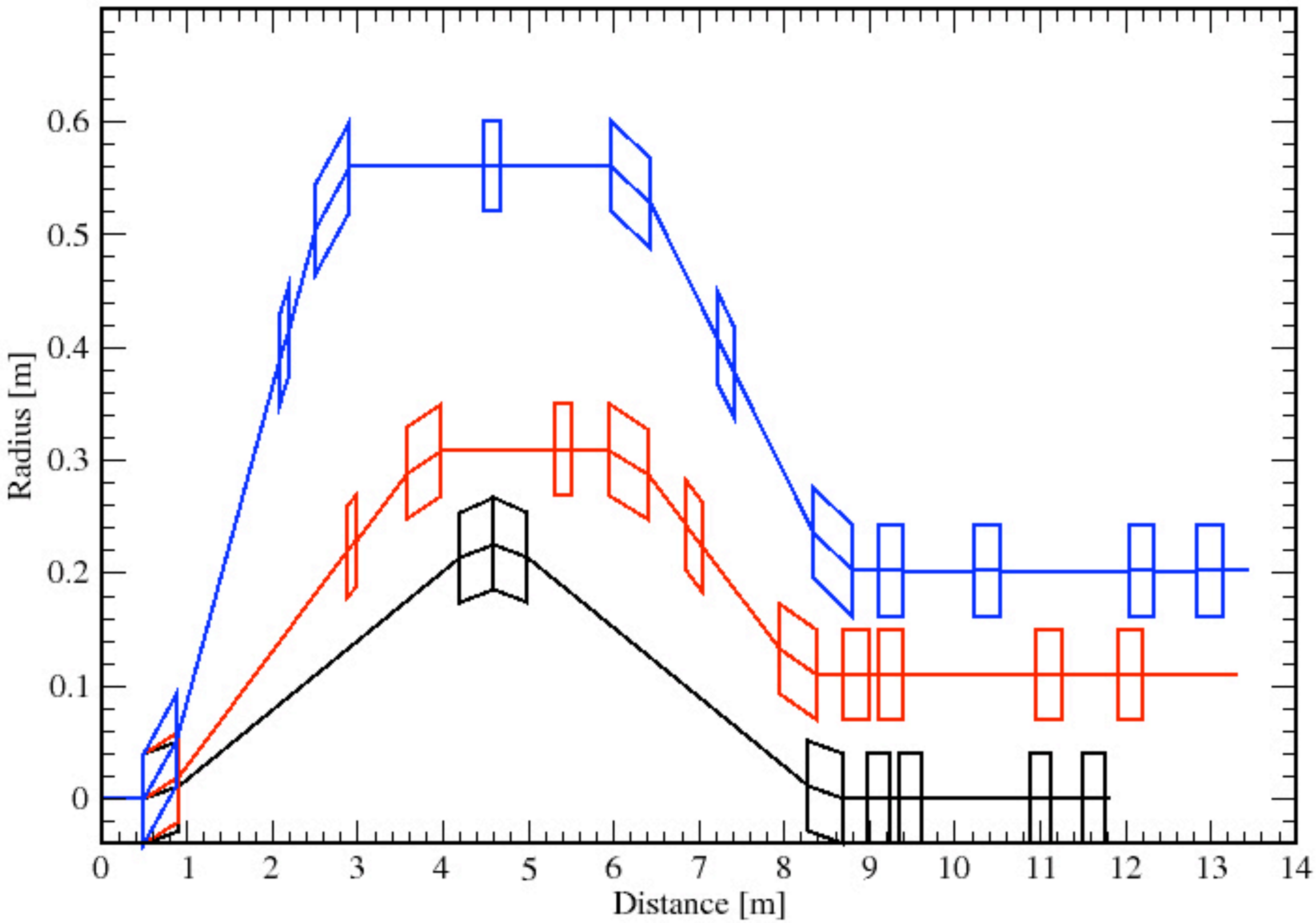
MeRHIC parameters for e-p collisions

© V.Ptitsyn

	not cooled		With cooling	
	p	e	p	e
Energy, GeV	250	4	250	4
Number of bunches	111		111	
Bunch intensity, 10^{11}	2.0	0.31	2.0	0.31
Bunch charge/current, nC/mA	32/320	5/**50**	32/320	5/**50**
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.5	7.3
rms emittance, nm	9.4	9.4	0.94	0.94
beta*, cm	50	50	50	50
rms bunch length, cm	20	0.2	5	0.2
beam-beam for p /disruption for e	1.5e-3	3.1	0.015	7.7
Peak Luminosity, 1e32, $cm^{-2}s^{-1}$	**0.93**		**9.3**	

Luminosity for light and heavy ions is the same as for e-p if measured per nucleon!

Vertical splitters – 3.35 GeV, 2.05 GeV, and 0.75 GeV



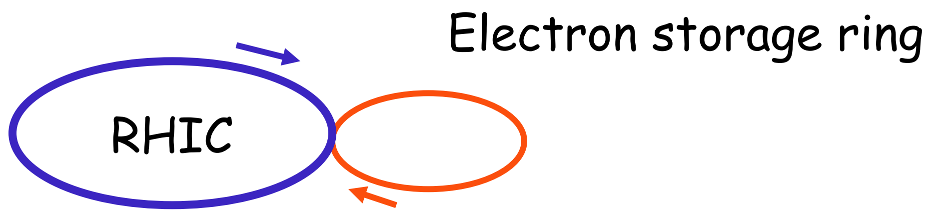
Main R&D Items

- **Electron beam R&D**
  - Energy recovery technology for high power beams (BNL)
    - R&D ERL - high current, low emittance beams, stability, low losses
    - Multi-cavity cryo-module development
  - High intensity polarized electron source (MIT & BNL)
    - Development of large cathode DC guns
      existing current densities ~ 50 mA/cm^2, good cathode lifetime.
    - Development of SRF polarized gun
  - Development of compact recirculating loop magnets (LDRD @ BNL)
    - Design, build and test a prototype of dipole and quadrupole
    - Design, build and test a prototype vacuum chamber
- **Main R&D items for hadron beams (BNL)**
  - Polarized ^{3}He production (EBIS) and acceleration
  - 166 bunches (50% more bunches in RHIC)
  - Proof-of-Principle of the Coherent Electron Cooling

<u>2007</u> Choosing the focus: ERL or ring for electrons?

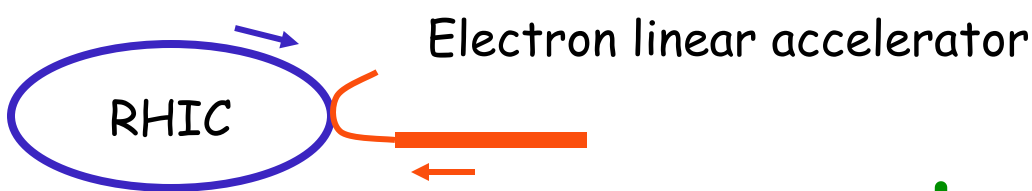
- Two main design options for eRHIC:
  - Ring-ring:

$$L = \left(\frac{4\pi\gamma_h\gamma_e}{r_h r_e}\right)(\xi_h\xi_e)\left(\sigma'_h\sigma'_e\right)f$$



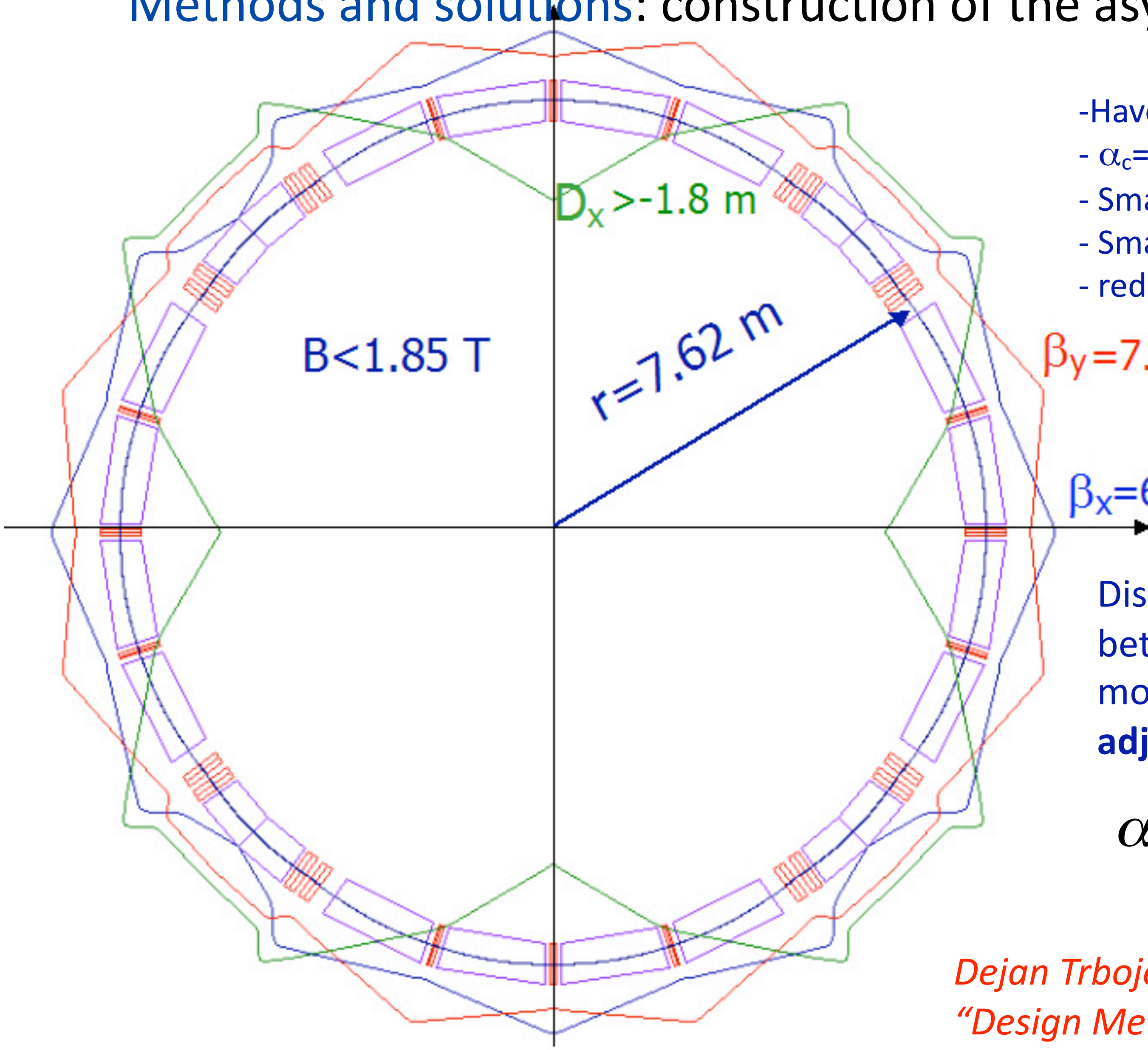
  - Linac-ring:

$$L = \gamma_h f\, N_h \frac{\xi_h Z_h}{\beta_h^* r_h}$$



L x 10

Methods and solutions: construction of the asynchronous arcs:



Goals:

- Have a good packing
- α_c=0 or M $_{5,6}$=0
- Small dispersion
- Small betatron functions
- reduce cost of civil construction

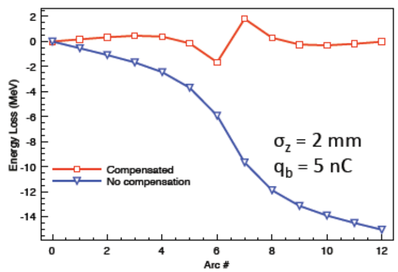
Dispersion function oscillates between ±1.8 m and the momentum compaction is **adjustable**:

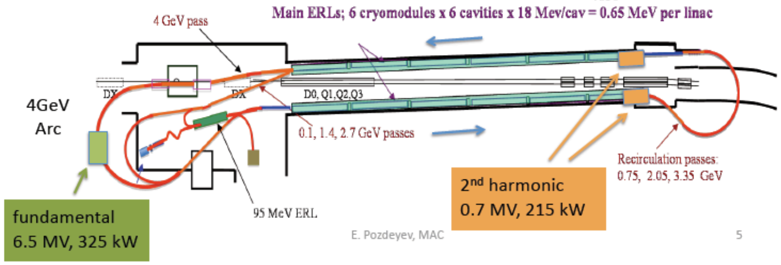
$$\alpha = \frac{1}{C_o}\int \frac{D}{\rho} ds \approx 0$$

Dejan Trbojevic: EPAC 1990, pp. 1536: "Design Method for High energy Accelerators without Transition Energy."

Energy loss and its compensation

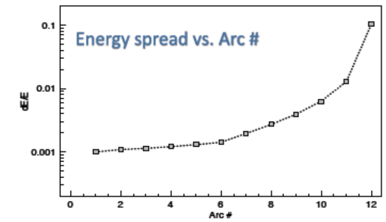
- **Total energy loss: 15.5 MeV**
  - Linac cavities: 6.5 MeV (0.54 MeV/linac)
  - Synch. radiation: 8.8 MeV
  - RW: 0.15 MeV, CSR: negligible
- **Total power loss: 765 kW**
- **Energy difference in arcs (max)**
  - Before compensation: 2%
  - After compensation: 0.06%

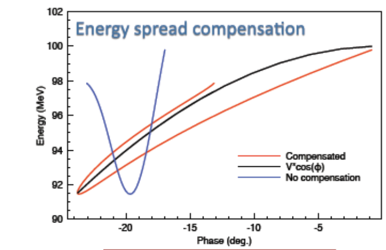


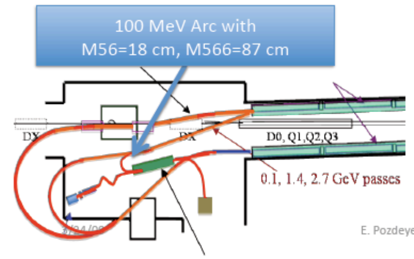


Energy spread and its compensation

	δE (MeV)
RF	0.17%
Cavity Wakes	8.9
Synch. Rad. (4•rms)	1.35
Resistive Wall	0.45
CSR	> 0.001
Total	10.7







100 MeV: 9 MeV -> 2 MeV
200 MeV: 9 MeV -> 3 MeV

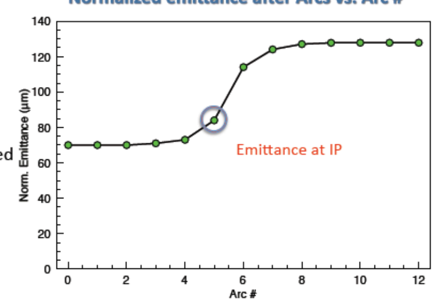
Transverse emittance growth

Synchrotron Radiation in Arcs

$$\delta\varepsilon = \frac{55 r_c \hbar c}{48\sqrt{3}mc^2}\gamma^5 \int_L \frac{H}{\rho^3} ds$$

- H function of 3.35 GeV arc is used
- H function and bending radius assumed the same for all arc

Normalized emittance after Arcs vs. Arc #



Transverse breakup due to short range wakes ("banana" effect): Work in progress

Beam losses

- **Touschek**
  - Total loss beyond ±6 MeV is 200 pA.
  - Small but, maybe, not negligible. We will look more carefully.
- **Scattering on residual gas (elastic)**
  - Total loss beyond 1 cm aperture at 100 MeV is 1 pA
  - Negligible
- **Bremsstrahlung on residual gas**
  - Total loss beyond ±6 MeV is < 0.1 pA
  - Negligible

(A. Fedotov, G. Wang)

Beam-Beam: kink instability

Without Landau damping, the beam parameters are above the threshold of kink instability for proton beam. Proper energy spread and chromaticity is needed to suppress the emittance growth.

To avoid strong head-tail instability:

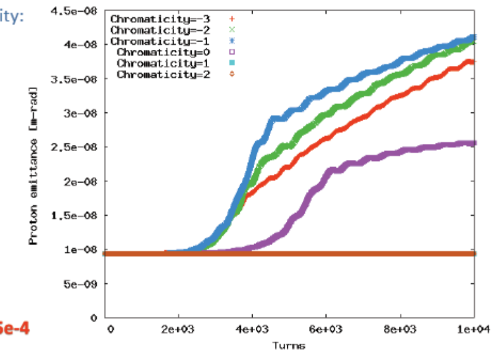
$$\frac{a\beta}{8\nu_s} < 1$$

$$a = \frac{\sigma_{pz}}{2 f_p f_z} = \frac{N_p N_e r_p r_e \sigma_{pz}}{2\sigma_{px}^2 \sigma_{ex}^2 \gamma_p \gamma_e}$$

Not Cooled MEeIC case

$$\frac{a\beta}{8\nu_s} \sim 2.5$$

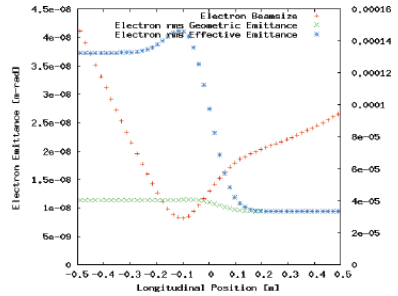
Chromaticity of 1 and dE/E of 5e-4
Suppress the instability



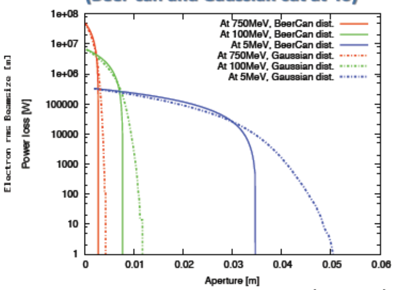
(Yue Hao)

Beam-Beam: electron beam disruption

Emittance growth in collision



Power loss if beam is not re-matched (Beer-can and Gaussian cut at 4σ)



(Yue Hao)

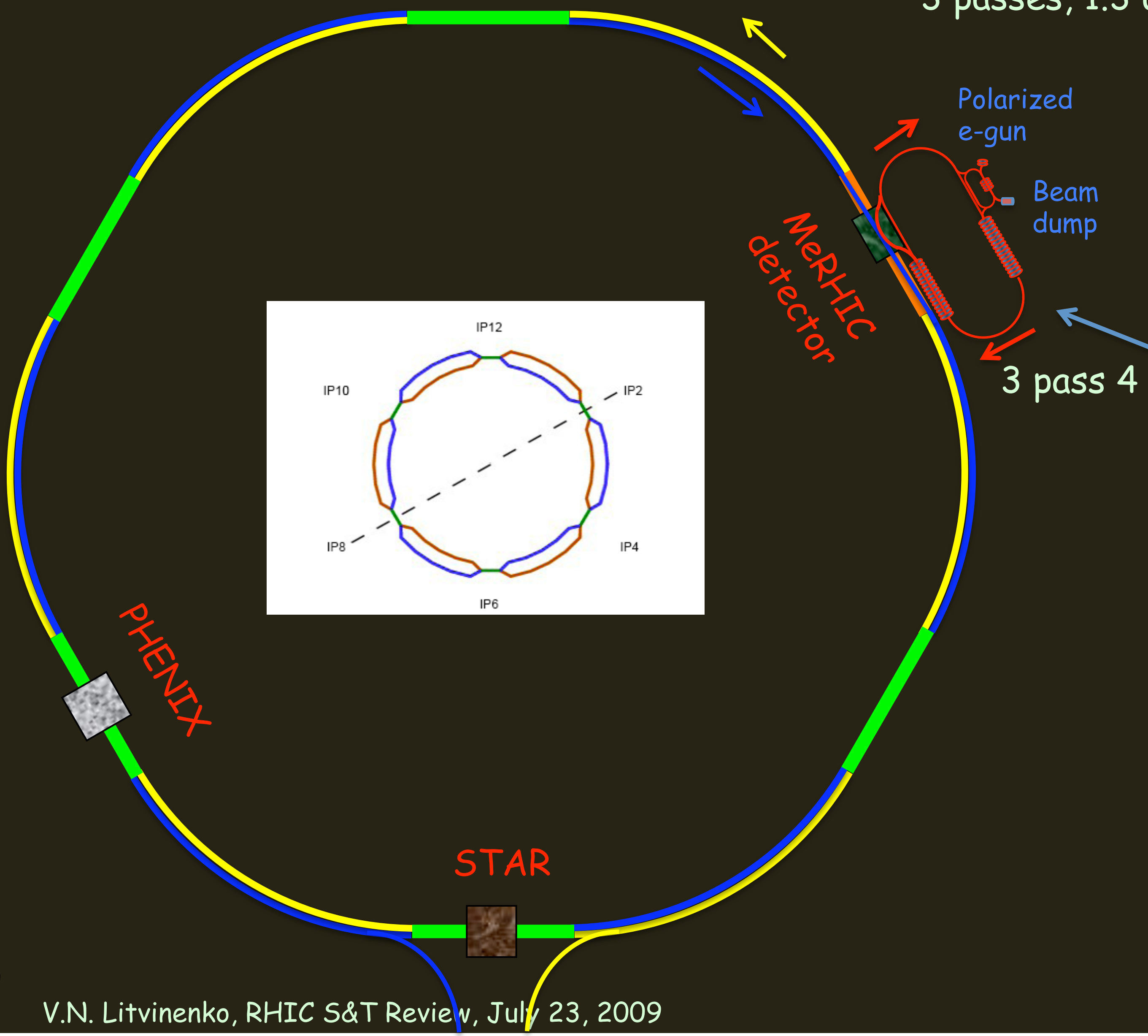
- **Growth of r.m.s. emittance is small. However, mismatch is large.**
- **Re-matching section might be required**
- **Re-matching section has to accommodate the RHIC abort gap (fast quad, electron lens)**

Possible future eRHIC up-grades and staging

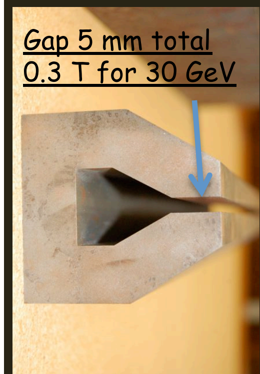
4 GeV e x 250 GeV p – 100 GeV/u Au

MeRHIC

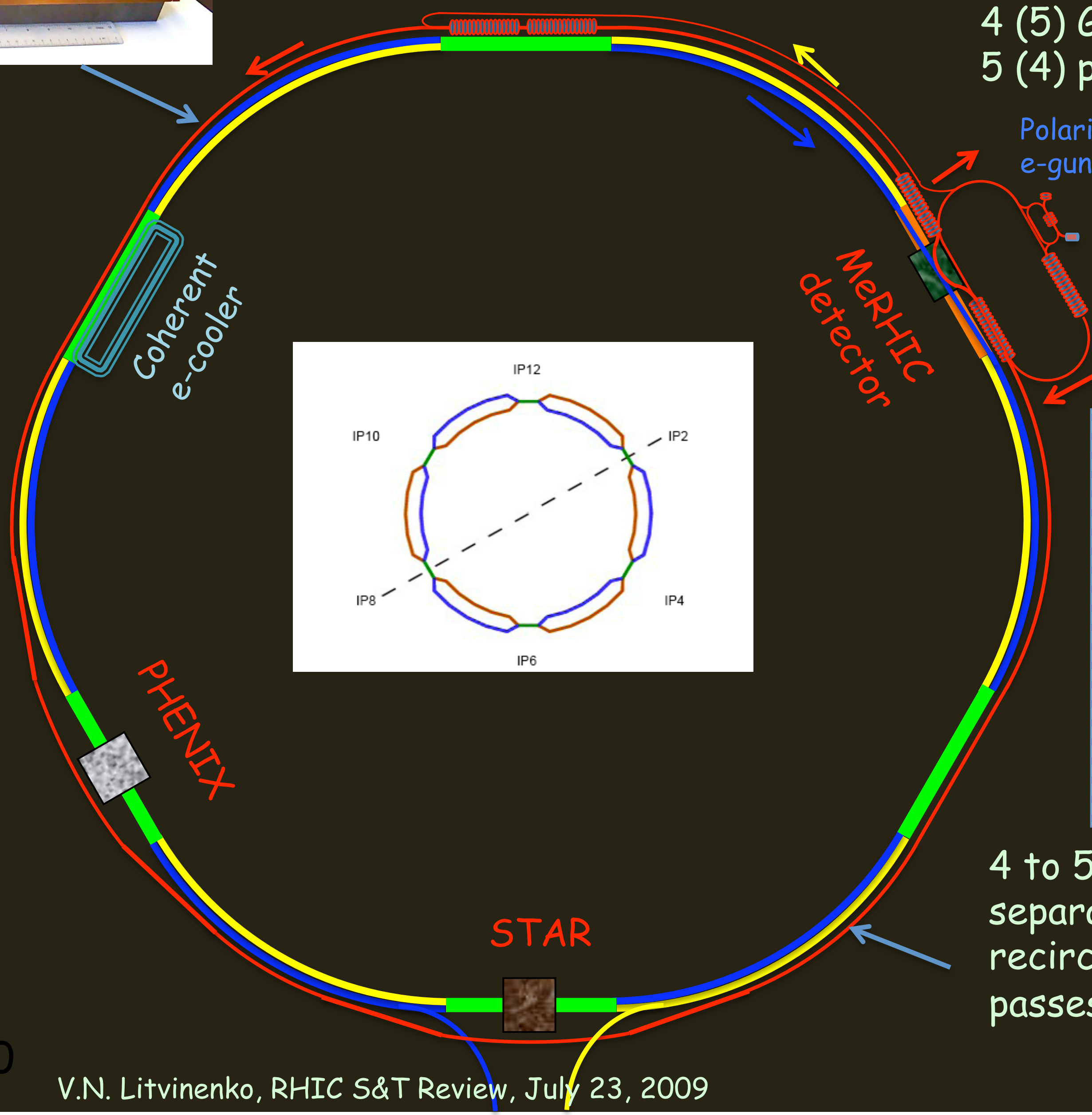
2 x 60 m SRF linac
3 passes, 1.3 GeV/pass

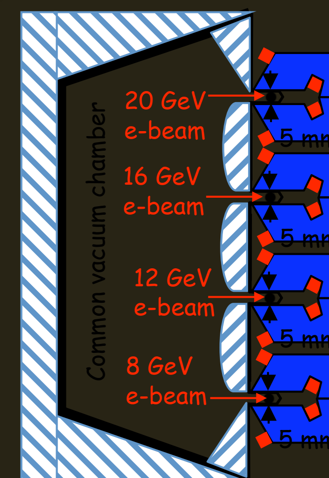


10 to 20 GeV e x 325 GeV p – 130 GeV/u Au eRHIC



2 x 200 m SRF linac
4 (5) GeV per pass
5 (4) passes

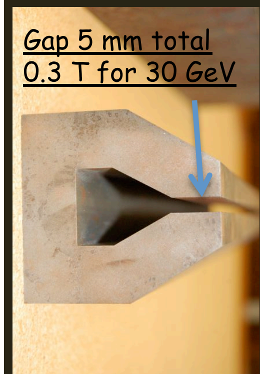




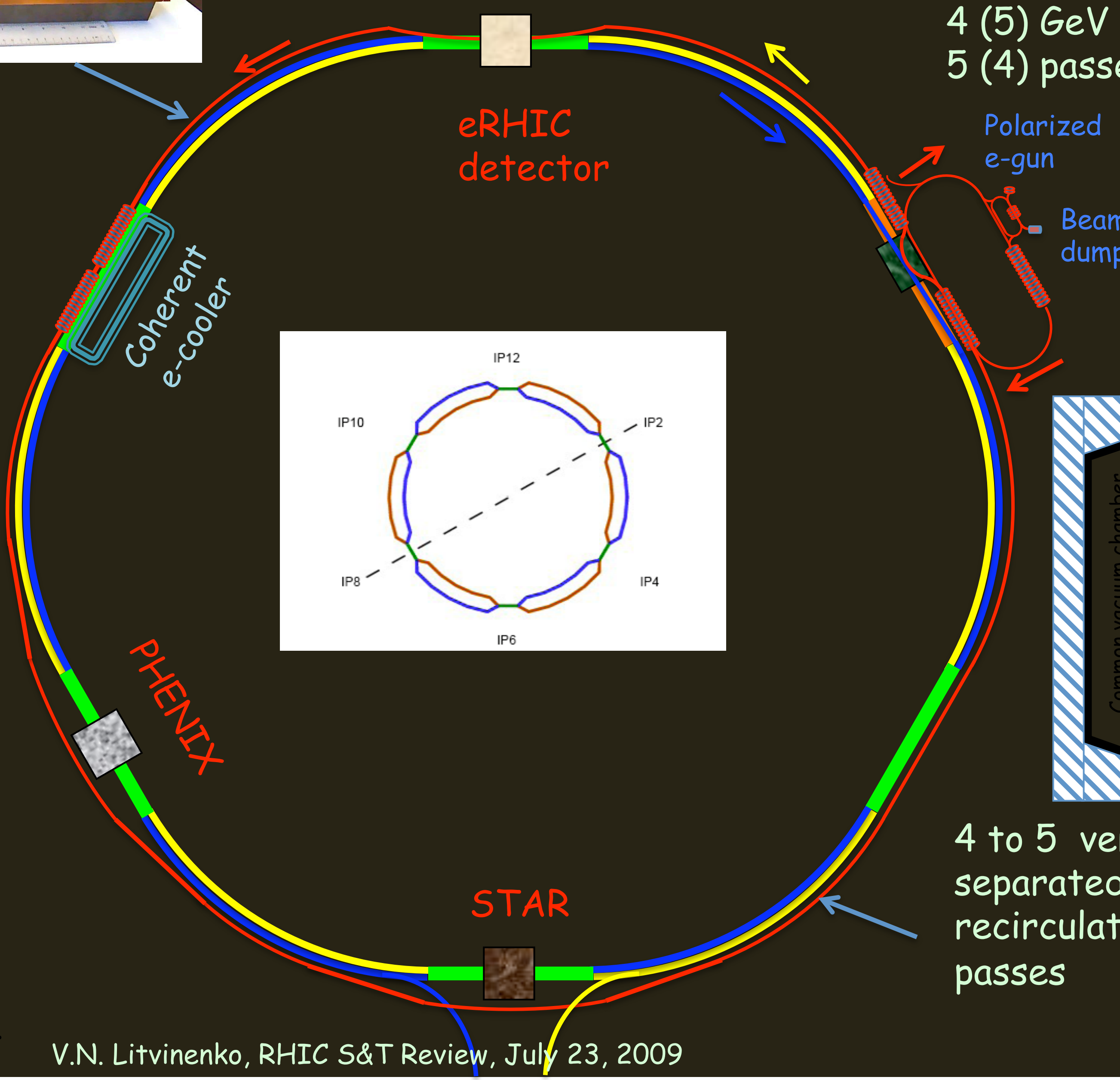
Possibility of 30 GeV low current operation

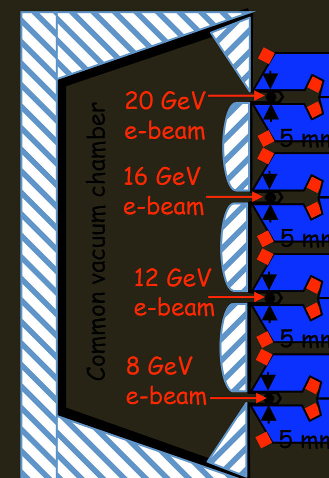
4 to 5 vertically separated recirculating passes

10 to 20 GeV e x 325 GeV p - 130 GeV/u Au
eRHIC



2 x 200 m SRF linac
4 (5) GeV per pass
5 (4) passes

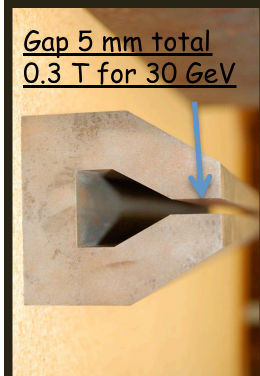




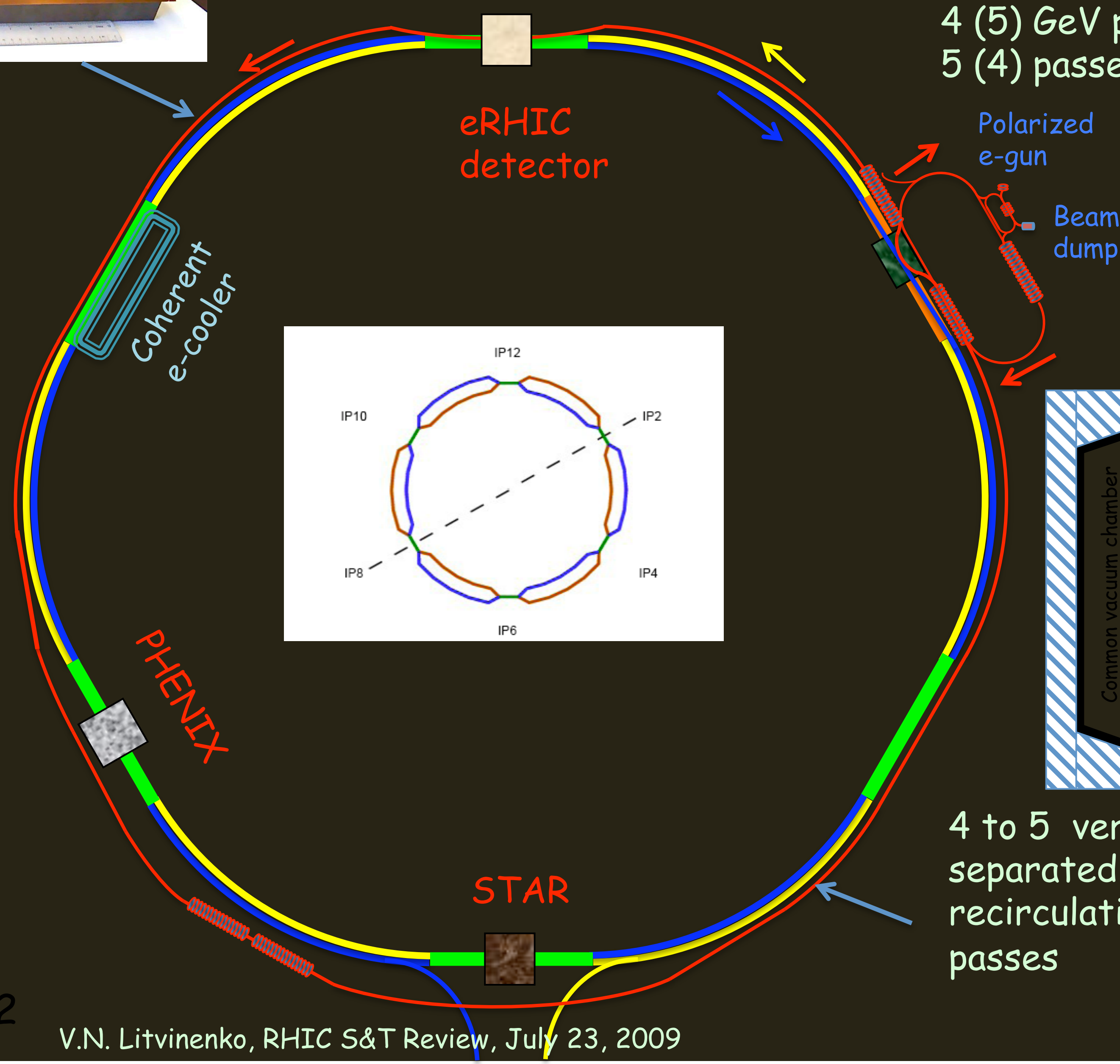
Possibility of 30 GeV low current operation

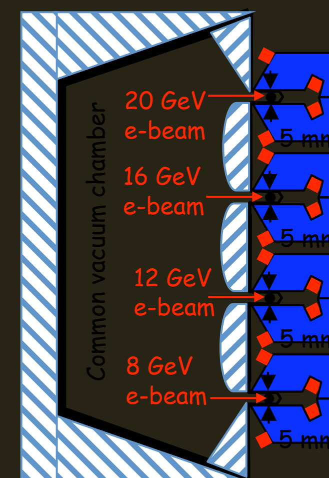
4 to 5 vertically separated recirculating passes

10 to 20 GeV e x 325 GeV p - 130 GeV/u Au
eRHIC



2 x 200 m SRF linac
4 (5) GeV per pass
5 (4) passes





Possibility of 30 GeV low current operation

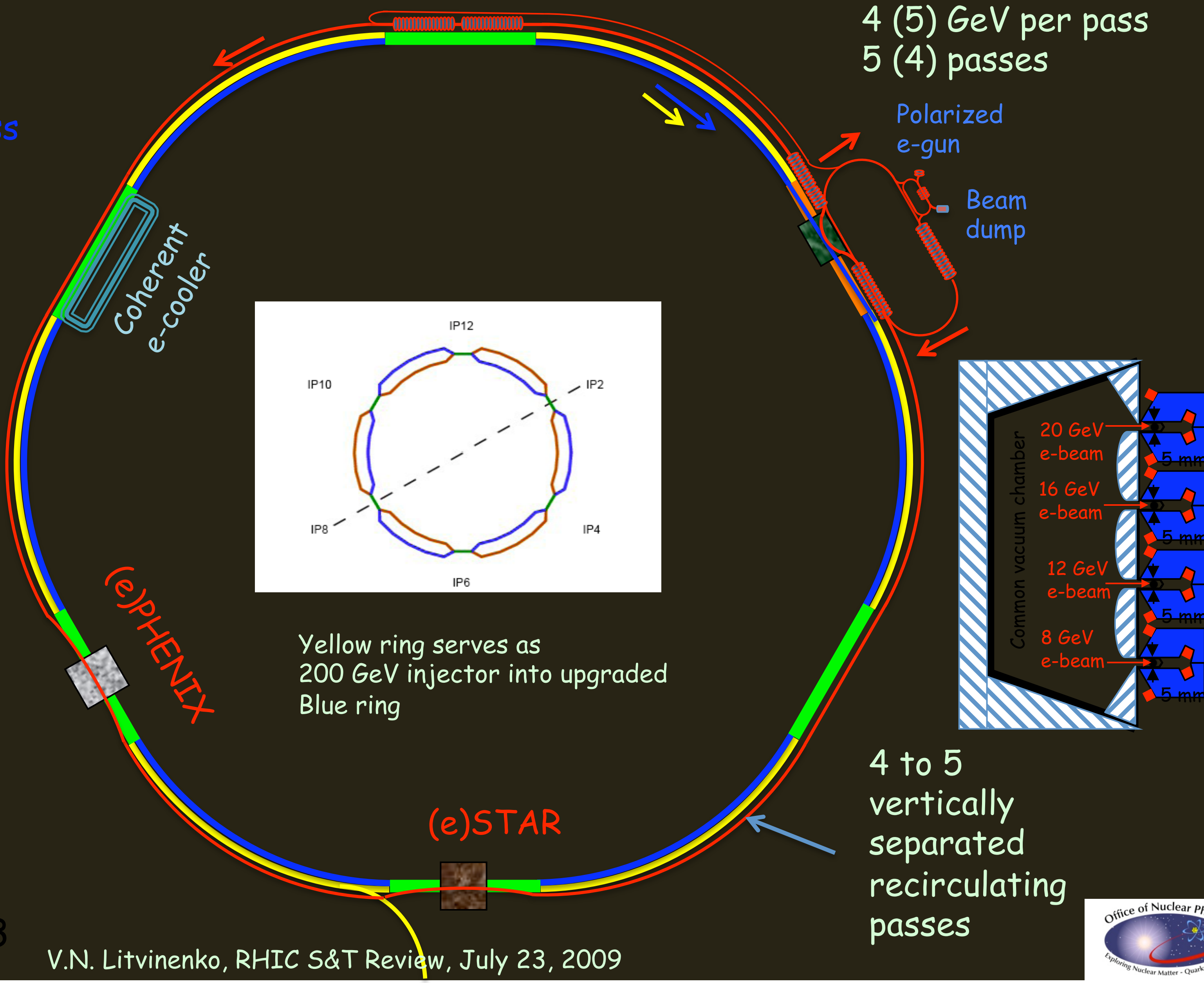
4 to 5 vertically separated recirculating passes

20 GeV e x 800 GeV p – 320 GeV/u U

eRHIC II

2 x 200 m SRF linac
4 (5) GeV per pass
5 (4) passes

Up-grade:
New LHC-class
SC magnets
in Blue ring



Possibility
of 30 GeV
low current
operation

4 to 5
vertically
separated
recirculating
passes

2008: Staging of eRHIC

- **MeRHIC**: Medium Energy eRHIC
  - Both Accelerator and Detector are located at IP2 of RHIC
  - 4 GeV e^- x 250 GeV p (45 or 63 GeV c.m.), L ~ 10^{32}-10^{33} cm^{-2} sec^{-1}
  - 90% of hardware will be used for HE eRHIC
- **eRHIC, High energy and luminosity phase,** inside RHIC tunnel

Full energy, nominal luminosity

  - Polarized 20 GeV e^- x 325 GeV p (160 GeV c.m), L ~ 10^{33}-10^{34} cm^{-2} sec^{-1}
  - 30 GeV e x 120 GeV/n Au (120 GeV c.m.), ~1/5 of full luminosity
  - and 20 GeV e x 120 GeV/n Au (120 GeV c.m.), full liminosity
- **eRHIC up-grades – if needed,** inside RHIC tunnel

Higher luminosity at reduced energy

  - Polarized 10 GeV e^- x 325 GeV p, L ~ 10^{35} cm^{-2} sec^{-1}

Or Higher energy operation with one new 800 GeV RHIC ring

  - Polarized 20 GeV e^- x 800 GeV p (~300 GeV c.m), L ~ 10^{34} cm^{-2} sec^{-1}
  - 30 GeV e x 300 GeV/n Au (~200 GeV c.m.), L ~ 10^{32} cm^{-2} sec^{-1}

Staging of eRHIC: Re-use, Beams and Energetics

- **MeRHIC**: Medium Energy electron-Ion Collider
  - 90% of ERL hardware will be use for full energy eRHIC
  - Possible use of the detector in eRHIC operation
- **eRHIC – High energy and luminosity phase**
  - **Based on present RHIC beam intensities**
  - With coherent electron cooling requirements on the electron beam current is 50 mA
  - 20 GeV, 50 mA electron beam losses 4 MW total for synchrotron radiation.
  - 30 GeV, 10 mA electron beam loses 4 MW for synchrotron radiation
  - Power density is <2 kW/meter and is well within B-factory limits (8 kW/m)
- **eRHIC upgrade(s)**
  - **High luminosity, low energy requires crab cavities, new injections, Cu-coating of RHIC vacuum chambers, new level of intensities in RHIC**
    - Polarized electron source current of 400 mA at10 GeV, losses 2 MW total for synchrotron radiation, power density is 1 kW/meter
  - **High energy option requires replacing one of RHIC ring with 8 T magnets**

eRHIC parameters

	MeRHIC		eRHIC with CeC		eRHIC II 8T RHIC	
	p (A)	e	p (A)	e	p/A	e
Energy, GeV	250 (100)	4	325 (125)	20 ‹30›	800 (300)	20 ‹30›
Number of bunches	111		166		166	
Bunch intensity (u) , 10^{11}	2.0	0.31	2.0 (3)	0.24	2.0 (3)	0.24
Bunch charge, nC	32	5	32	4	32	4
Beam current, mA	320	50	420	50 ‹5›	420	50 ‹5›
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.2	18	1	10
Polarization, %	70	80	70	80	70 (?)	80
rms bunch length, cm	20	0.2	4.9	0.2	4.5	0.2
β^*, cm	50	50	25 (5)	25 (5)	25 (5)	25 (5)
Luminosity, x 10^{33}, $cm^{-2}s^{-1}$	0.1 -> 1 with CeC		2.8 (14)		6 (30)	

‹ Luminosity for 30 GeV e-beam operation will be at 10% level›